

U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

PB-258 874

Mechanism and Kinetics of the Formation
of NO_x and Other Combustion Pollutants.
Phase I. Unmodified Combustion

Exxon Research and Engineering Co, Linden, N J

Prepared for

Industrial Environmental Research Lab, Research Triangle Park, N C

Aug 76

EPA

U.S. Environmental Protection Agency
Office of Research and Development

Industrial Environmental Research
Laboratory
Research Triangle Park, N.C. 27711

PB 258 874

EPA-600/7-76-009a
August 1976

**MECHANISM AND KINETICS OF
THE FORMATION OF NO_x
AND OTHER
COMBUSTION POLLUTANTS:
Phase I. Unmodified Combustion**

Interagency
Energy-Environment
Research and Development
Program Report



TECHNICAL REPORT DATA (Please read Instructions on the reverse before completing)			
1. REPORT NO. EPA-600/7-76-009a		3. RECIPIENT'S ACCESSION NO.	
4. TITLE AND SUBTITLE MECHANISM AND KINETICS OF THE FORMATION OF NO_x AND OTHER COMBUSTION POLLUTANTS; Phase I. Unmodified Combustion		5. REPORT DATE August 1976	
7. AUTHOR(S) V. S. Engleman and W. Bartok		6. PERFORMING ORGANIZATION CODE	
9. PERFORMING ORGANIZATION NAME AND ADDRESS Exxon Research and Engineering Co. P. O. Box 8 Linden, New Jersey 07036		8. PERFORMING ORGANIZATION REPORT NO. GRU. 2DJAM. 76	
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development Industrial Environmental Research Laboratory Research Triangle Park, NC 27711		10. PROGRAM ELEMENT NO. 1AB014; ROAP 21BCC-013	
		11. CONTRACT/GRANT NO. 68-02-0224	
		13. TYPE OF REPORT AND PERIOD COVERED Phase I Final; 4/73-2/74	
		14. SPONSORING AGENCY CODE EPA-ORD	
15. SUPPLEMENTARY NOTES Project officer for this report is W. S. Lanier, 919/549-8411 Ext 2432, Mail Drop 65.			
16. ABSTRACT The report gives Phase I results of an investigation of the mechanisms and kinetics of the formation of NO_x and other combustion pollutants. It gives results of experimental investigations of unmodified combustion and supporting theoretical calculations. The combustion of hydrogen, carbon monoxide, methane, and propane with air in a jet-stirred combustor (JSC) was studied to facilitate the assessment of coupled combustion/pollutant formation. The JSC tests also extended the range and accuracy of data taken in previous studies. Experiments also included a flow reactor capable of accepting multiple burner types and operating with selected wall temperature. Premixed flat and focused flames, as well as laminar and turbulent diffusion flames, were studied in the flow reactor using methane and propane fuels. The tests included heat-loss and adiabatic conditions and a limited number of wall heat addition cases. Stirred reactor calculations, supporting the experimental program, indicated the need for more detailed kinetics in hydrocarbon/air combustion before NO_x formation can be predicted. Similarly, plug flow calculations indicated strong coupling between combustion reactions, specie diffusion, and NO_x formation in the flame zone. Further kinetic data on reactions between hydrocarbon fragments and nitrogenous species is required to properly assess the importance of those interactions in NO_x formation.			
17. KEY WORDS AND DOCUMENT ANALYSIS			
a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air Pollution Reaction Kinetics Combustion Nitrogen Oxides Methane Propane		Hydrogen Carbon Monoxide Mathematical Models Diffusion Flames	Air Pollution Control Stationary Sources Well Stirred Reactor Plug Flow Reactor Unmodified Combustors
			13B 07D 21B 07B 07C 12A
18. DISTRIBUTION STATEMENT Unlimited		19. SECURITY CLASS (This Report) Unclassified	21. NO. OF PAGES 310
		20. SECURITY CLASS (This page) Unclassified	22. PRICE

RESEARCH REPORTING SERIES

Research reports of the Office of Research and Development, U.S. Environmental Protection Agency, have been grouped into seven series. These seven broad categories were established to facilitate further development and application of environmental technology. Elimination of traditional grouping was consciously planned to foster technology transfer and a maximum interface in related fields. The seven series are:

1. Environmental Health Effects Research
2. Environmental Protection Technology
3. Ecological Research
4. Environmental Monitoring
5. Socioeconomic Environmental Studies
6. Scientific and Technical Assessment Reports (STAR)
7. Interagency Energy-Environment Research and Development

This report has been assigned to the INTERAGENCY ENERGY-ENVIRONMENT RESEARCH AND DEVELOPMENT series. Reports in this series result from the effort funded under the 17-agency Federal Energy/Environment Research and Development Program. These studies relate to EPA's mission to protect the public health and welfare from adverse effects of pollutants associated with energy systems. The goal of the Program is to assure the rapid development of domestic energy supplies in an environmentally-compatible manner by providing the necessary environmental data and control technology. Investigations include analyses of the transport of energy-related pollutants and their health and ecological effects; assessments of, and development of, control technologies for energy systems; and integrated assessments of a wide range of energy-related environmental issues.

REVIEW NOTICE

This report has been reviewed by the participating Federal Agencies, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the Government, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

EPA-600/7-76-009a

August 1976

MECHANISM AND KINETICS
OF THE FORMATION OF NO_x
AND OTHER COMBUSTION POLLUTANTS
PHASE I. UNMODIFIED COMBUSTION

by

V.S. Engleman and W. Bartok

Exxon Research and Engineering Company
P.O. Box 8
Linden, New Jersey 07036

Contract No. 68-02-0224
ROAP No. 21BCC-013
Program Element No. 1AB014

EPA Project Officer: W. Steven Lanier

Industrial Environmental Research Laboratory
Office of Energy, Minerals, and Industry
Research Triangle Park, NC 27711

Prepared for

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Research and Development
Washington, DC 20460

TABLE OF CONTENTS

	<u>Page</u>
FOREWORD	i (d)
SUMMARY.	1
1. INTRODUCTION	2
2. EXPERIMENTAL PROCEDURES AND RESULTS.	3
2.1 Jet-Stirred Combustor	3
2.2 The Multiburner	16
2.2.1 The Multiburner Furnace.	16
2.2.2 Burner Design.	18
2.2.3 Sampling and Gas Analysis.	22
2.2.4 Data Reduction	22
2.2.5 Results for Premixed Flames.	27
2.2.6 Results for Diffusion Flames	31
3. THEORETICAL CALCULATIONS	37
3.1 Equilibrium Calculations on Premixed Flames	37
3.2 Survey of Coupled NO _x /Combustion Kinetics	37
3.3 Kinetics Calculations	44
3.4 Results of Theoretical Calculations for Methane/Air	61
3.4.1 80% Stoichiometric Air	61
3.4.2 100% Stoichiometric Air.	62
3.4.3 120% Stoichiometric Air.	66
3.5 Discussion.	66
3.6 Reactions of Importance at the Interface Between the Branching Zone and the Relaxation Zone.	69
3.7 Comparison of Theoretical Calculations with Experimental Results.	72
4. CONCLUSIONS.	74
APPENDIX A - MASTER LIST OF REACTIONS FOR 25 ALLOWED SPECIES	A-1
APPENDIX B - CROSS INDEX OF REACTIONS FOR 25 SPECIES	B-1
APPENDIX C - KINETIC DATA ANALYSIS FOR JET-STIRRED COMBUSTOR	C-1
APPENDIX D - NO/NO _x PLOTS.	D-1
APPENDIX E - CO/CO ₂ /HC/O ₂ DATA PLOTS	E-1
APPENDIX F - DATA LISTINGS	F-1

FOREWORD

This report summarizes the results of Phase I of a study on the "Definition of the Mechanism and Kinetics of the Formation of NO_x and Other Pollutants under Normal and Combustion Modification Conditions". This study was conducted by Exxon Research and Engineering Company under Contract 68-02-0224 funded by the Environmental Protection Agency.

The helpful comments and suggestions of Messrs. W. S. Lanier, G. B. Martin, and D. W. Pershing, project officers for this contract, are gratefully acknowledged. The skillful assistance of Messrs. F. D. Remyn and R. M. Buono in conducting the laboratory portion of this program is also acknowledged.

SUMMARY

The objective of this study was to investigate the mechanism and kinetics of the formation of NO_x and other pollutants in combustion. A combined experimental and theoretical study was undertaken for this purpose. This report covers Phase I, the study of combustion under unmodified conditions and calculations using the best available kinetic data from the literature.

A jet-stirred combustor was used to extend the range and accuracy of data taken in previous studies. Since precise measurements of concentrations and temperatures are critical to allow meaningful results in combustion calculations for a well-stirred reactor, additional studies on the combustion of hydrogen, carbon monoxide, methane, and propane with air were made. These studies of coupled combustion/pollutant formation indicated substantial heat loss from a conventional stirred reactor and the need for the development of an adiabatic stirred combustor.

A furnace capable of studying combustion under adiabatic conditions (called the multiburner because it was designed for multifuel firing capability in the same combustion zone) was further refined for these studies. This unit is an electrically-heated furnace with a zirconia muffle tube that is capable of attaining temperatures up to about 2500°K . Premixed flames of the flat-flame and focused-flame type as well as laminar and turbulent diffusion flames were studied using methane and propane as fuels. These studies included both adiabatic and heat-loss conditions. In addition, a few runs were made with wall temperatures above the adiabatic flame temperatures.

Both stirred reactor and plug flow calculations were made. Stirred reactor calculations indicated the need for more detailed kinetics in hydrocarbon-air combustion for the prediction of NO_x formation. Plug flow calculations (with kinetic data available from the literature at the time) indicated strong coupling between combustion reactions and NO_x formation in the flame zone. However, since no reaction rate data were available to test the direct coupling between hydrocarbon fragments and nitrogenous species, further elucidation of the kinetics is required to determine the importance of such reactions for NO_x formation.

1. INTRODUCTION

Under Contract No. 68-02-0224, sponsored by the Environmental Protection Agency, Exxon Research and Engineering Company conducted a study to relate the kinetics and mechanism of pollutant formation reactions and those of hydrocarbon reactions. The emphasis in this program was placed on NO_x formation and destruction reactions as they relate to hydrocarbon combustion. This program was performed in two phases. This report covers the work in Phase I which included studies of unmodified combustion in a non-adiabatic stirred combustor and a plug flow combustor capable of adiabatic operation. Preliminary kinetics calculations based on the most complete kinetic data available from the literature at the time were also conducted in Phase I. Phase II, which is covered in a companion report, included experimental studies of modified combustion in a plug flow system as well as studies in a newly developed adiabatic stirred combustor. Kinetics calculations, using updated literature information as well as estimates for potentially important reactions not available from the literature, were also performed.

The purpose of these studies was to provide further understanding of the coupling between combustion reactions and pollutant formation (with emphasis on NO_x) leading to the capability to perform accurate predictive calculations on complex combustion systems. The ultimate aim of this and other fundamental combustion research studies being conducted for the Combustion Research Branch of the Industrial Environmental Research Laboratory of EPA is developed control technology for stationary sources.

Clearly, in a practical system, there will be interactions among chemistry, fluid mechanics and heat transfer. However, without an understanding of the basic chemistry of combustion, agreement between theory and experiment in a particular case may be fortuitous and will not allow application of the same theory to a new system. Thus, the theory becomes merely an empirical correlation. These studies on the chemistry of combustion/pollutant formation were therefore undertaken, in order to progress towards a theory of general applicability to a wide variety of combustion systems. These studies were oriented toward studying combustion under idealized conditions, either controlled by chemical kinetics or with minimum, or well-defined fluid mechanic and heat transfer interactions.

2. EXPERIMENTAL PROCEDURES AND RESULTS

Two experimental devices were used in the experimental portion of this study: (1) the jet-stirred combustor--non-adiabatic stirred reactor capable of operating under kinetically-limited combustion conditions and (2) the multiburner--plug flow reactor, with interchangeable burners, capable of operating under adiabatic conditions. This section covers the experimental portion of the study, while the theoretical considerations will be discussed in the following section.

2.1 Jet-Stirred Combustor

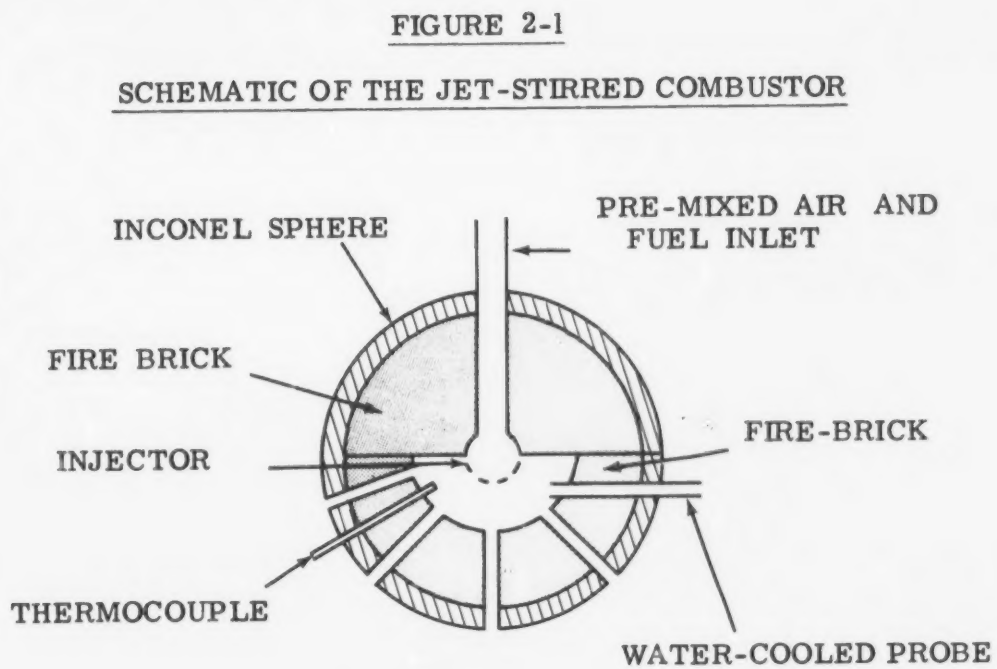
The jet-stirred combustor used in this program is a modification of the Longwell-Weiss reactor (2-1) with hemispherical geometry. This device was selected because it has been used extensively in fluid mechanic and combustion modeling and because the combustion rates are limited by chemical kinetics as opposed to transport effects (2-2). The apparatus used was described in the Final Report for the preceding program (conducted under Contract No. CPA 70-90, Reference 2-3) whose purpose was to investigate the basic factors affecting nitric oxide formation in the combustion of fossil fuels. The reactor (Figure 2-1) consists of an outer shell of fire-brick shaped as two halves of a sphere three inches in diameter. The upper hemisphere is solid with the exception of the hole through which the reactants are brought to the injector. The lower hemisphere is hollowed out to a reaction zone of 1.5 inch diameter. The insulating shell has twenty-five holes of 0.125 inch diameter, through which the burned mixture exits.

Fuel and air are metered separately through calibrated rotameters, preheated to the desired inlet temperature and then mixed before entering the combustor. The temperature of the fuel/air stream is measured immediately before injection. The fuel-air mixture enters the reaction zone through a stainless steel injector which is a hemisphere into which are drilled forty radial holes of 0.020 inch diameter. The reactants enter the reaction zone as small sonic jets which stir the reactor contents and produce a mixture of essentially uniform temperature and composition in a characteristic time which is short compared with the average residence time. The combustion experiments were conducted at atmospheric pressure with a range of residence times from 1-1/2 to 4 milliseconds.

2-1 Longwell, J. P. and Weiss, M. A., Ind. Eng. Chem. 47, 1634 (1955).

2-2 Hottel, H. C., Williams, G. C., and Miles, G. A., Eleventh Symposium (International) on Combustion, p. 771, The Combustion Institute, 1967.

2-3 Bartok, W., Engleman, V. S., and del Valle, E. G., Laboratory Studies and Mathematical Modeling of NO_x Formation in Combustion Processes, Final Report EPA Contract CPA 70-90, December 1971.



Gas temperatures were measured up to temperatures slightly in excess of 2000°K with a Pt/Pt-10% Rh thermocouple 0.010 inches diameter. Radiation corrections were found to be negligible because of the intense stirring in the combustion zone (see Appendix C). Duplicate runs were made with silica coated and uncoated thermocouples in selected cases to check for catalytic effects on temperature measurements. No measurable differences were found. The thermocouple was movable so that traverses could be taken during a run. It was found that the temperatures were quite uniform throughout the reaction zone although slightly cooler in the immediate vicinity of the injector sphere and in the immediate vicinity of the outer wall when the thermocouple was drawn back into its port.

The combustion gases were sampled through a water-cooled stainless steel probe, 0.125 inches outside diameter and 0.033 inches inside diameter similar to that used by Longwell and Weiss (2-1). The probe was placed through a port in the shell of the combustor. The quenched gases were pumped through a diaphragm pump to the combustion gas analyzers. The most important species analysis in this study was the measurement of NO_x concentrations. During the preceding program (CPA 70-90, Reference 2-3) these analyses were performed primarily with the Envirometrics Multigas Analyzer although cross-checks were made with the DuPont Photometric NO_x analyzer. During the present program (68-02-0224) a Thermo Electron Chemiluminescence Analyzer was used and the results of both programs served as cross-checks of the data. Care had to be taken when using the Envirometrics analyzer in the presence of CO, although since the response time to CO is slower than the response time to NO_x, CO concentrations of up to 5-10% could be handled with minimum interference by cyclic sampling/purge techniques which took advantage of the different response times for NO_x and for CO.

The hydrogen was Linde extra dry grade with a stated minimum purity of 99.95%, the carbon monoxide was Matheson C.P. grade with a stated minimum purity of 99.5% and the propane was Matheson C.P. grade with a stated minimum purity of 99.0%. The air was Baker dry grade manufactured by mixing nitrogen and oxygen with a typical argon concentration of 450 ppm. The oxygen concentration of each cylinder was measured and was generally found to be 21.0%.

Precise experimental measurements of concentrations and temperature are extremely critical for achieving meaningful results in combustion calculations for a well-stirred reactor. To assure the precise nature of the measurements made in the preceding program (reference 2-3) and to extend those measurements to include those parameters necessary for kinetic calculations for the assessment of the importance of combustion intermediates in coupled combustion/pollutant formation, further studies were made with the jet-stirred combustor for hydrogen, carbon monoxide, methane, and propane.

Temperature measurements for methane/air combustion are shown in Figures 2-2 and 2-3. Figure 2-2 shows temperature vs. mixture ratio with the solid line being the same one indicated in reference 2-3. The dotted line is the extension of this line to fuel-rich conditions with the peak indicated at about 90% stoichiometric air. In reference 2-3 temperature measurements were taken only under fuel lean conditions at these flow rates. An indication of the temperature uniformity within the

FIGURE 2-2

TEMPERATURE AS A FUNCTION OF MIXTURE RATIO
JET-STIRRED COMBUSTOR / METHANE - AIR

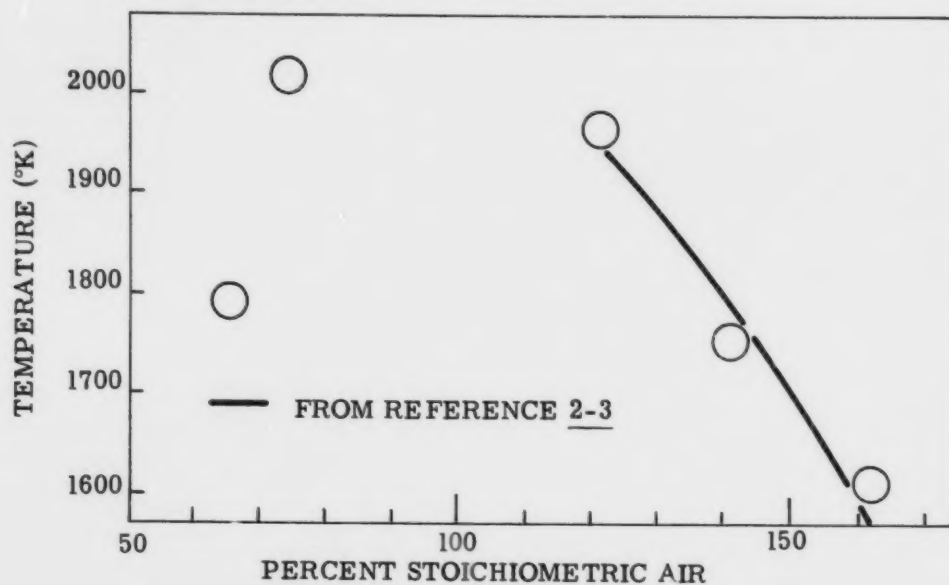
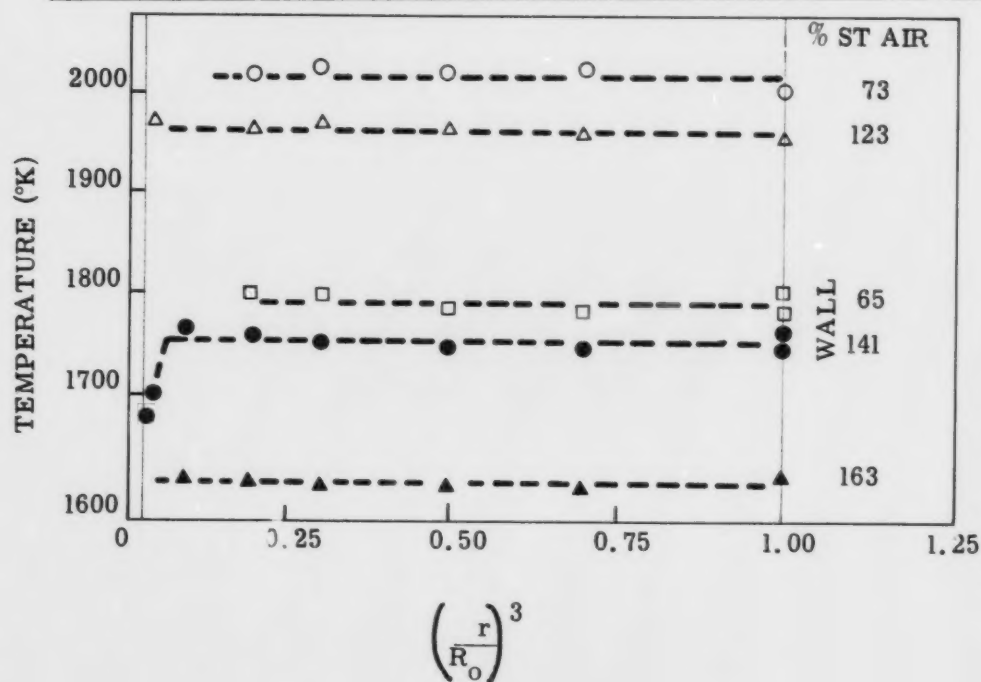


FIGURE 2-3

TEMPERATURE PROFILES AT REPRESENTATIVE STOICHIOMETRIES
JET-STIRRED COMBUSTOR / METHANE - AIR



jet-stirred combustor with methane is given in Figure 2-3. Temperature is plotted against $(r/R_0)^3$, a normalized volumetric parameter, indicating the portion of the reactor volume at a given temperature. It can be seen that the temperatures are quite uniform throughout the combustor. Near the injector sphere the temperature apparently drops off but this is probably caused by a combination of convective cooling by the cool inlet jets in the vicinity of the injector sphere and radiative cooling of the thermocouple bead by the injector sphere. The temperatures used for kinetics calculations are indicated by the horizontal dashed lines.

The NO_x emissions from the jet-stirred combustor with methane/air are indicated in Figure 2-4. It should be noted that peak NO_x formation occurs under slightly fuel-rich conditions. These data were measured with a Thermo-electron NO/NO_x chemiluminescence analyzer and are in very good agreement with the results obtained in reference 2-3 using Envirometrics electrochemical analyzers and a DuPont photometric analyzer.

The oxygen results were obtained with a polarographic oxygen analyzer. They are shown in Figure 2-5 and compare favorably with those reported in reference 2-3 which were taken with a paramagnetic oxygen analyzer. The results are in good agreement with calculated values of residual oxygen in a well-stirred combustor.

The effect of the water-cooled sampling probe on the temperature of the jet-stirred combustor is dramatic if species probe traverses are attempted. As long as the probe is outside the volume of the reactor (up to a position flush with the wall) the temperature in the reactor remains fairly constant. As the probe enters the reaction zone, the temperature begins to drop, and it drops more than 100 K by the time the probe is three fourths of the way to the center of the reactor. This is illustrated in Figure 2-6 for which the uncooled thermocouple probe was held in a fixed position while the cooled species sampling probe was inserted into the reactor.

Temperature measurements for carbon monoxide/air combustion are shown in Figures 2-7 and 2-8. Figure 2-7 shows temperature vs. mixture ratio with the solid line being the one calculated on a theoretical basis as indicated in the paper presented at the Fourteenth Combustion Symposium and shown in Appendix C. The data have been extended on the fuel rich side beyond the data available at the time of writing the Combustion Symposium paper. The temperature uniformity in the combustion zone for carbon monoxide air is also good as indicated in Figure 2-8. The temperatures used for kinetics calculations are indicated by the horizontal dashed lines.

The NO_x emissions for CO/air are shown in Figure 2-9 and were taken with a chemiluminescence analyzer. The agreement with the results reported in reference 2-3 is quite good on the lean side. There is some disagreement under fuel rich conditions between 50 and 65% stoichiometric air but the present results should be considered more reliable because the CO content in the exhaust exceeds 10%. That high a concentration is difficult to eliminate as an interference with the NO_x Faristor (even with the special cyclic sampling techniques developed (2-3)) when the NO_x level is below 50 ppm; the chemiluminescent analyzer does not have such a CO interference.

FIGURE 2-4

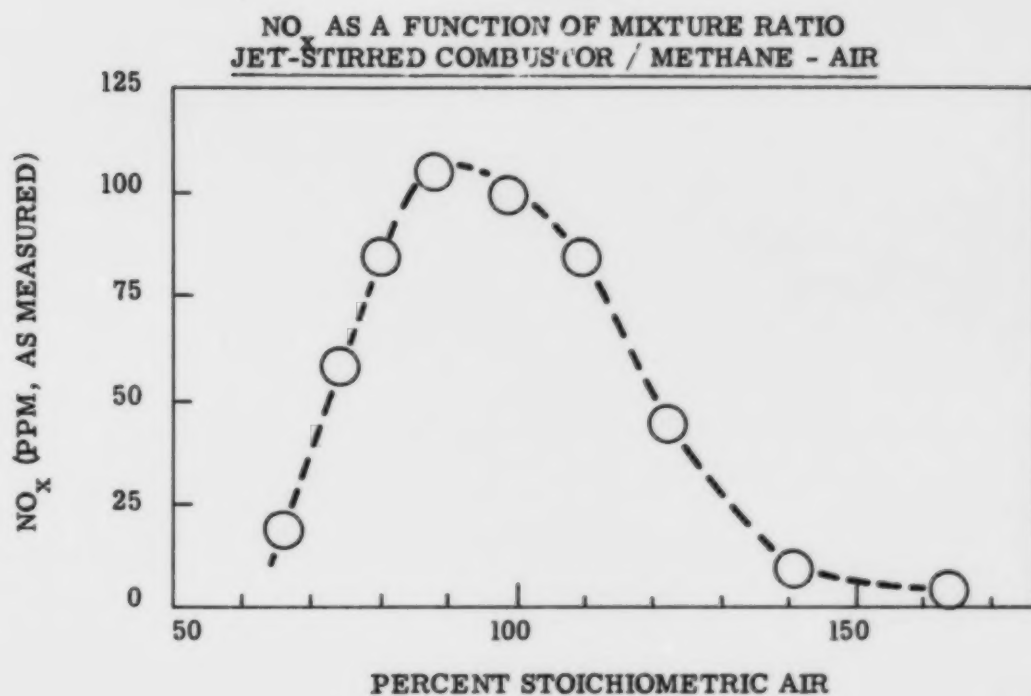


FIGURE 2-5

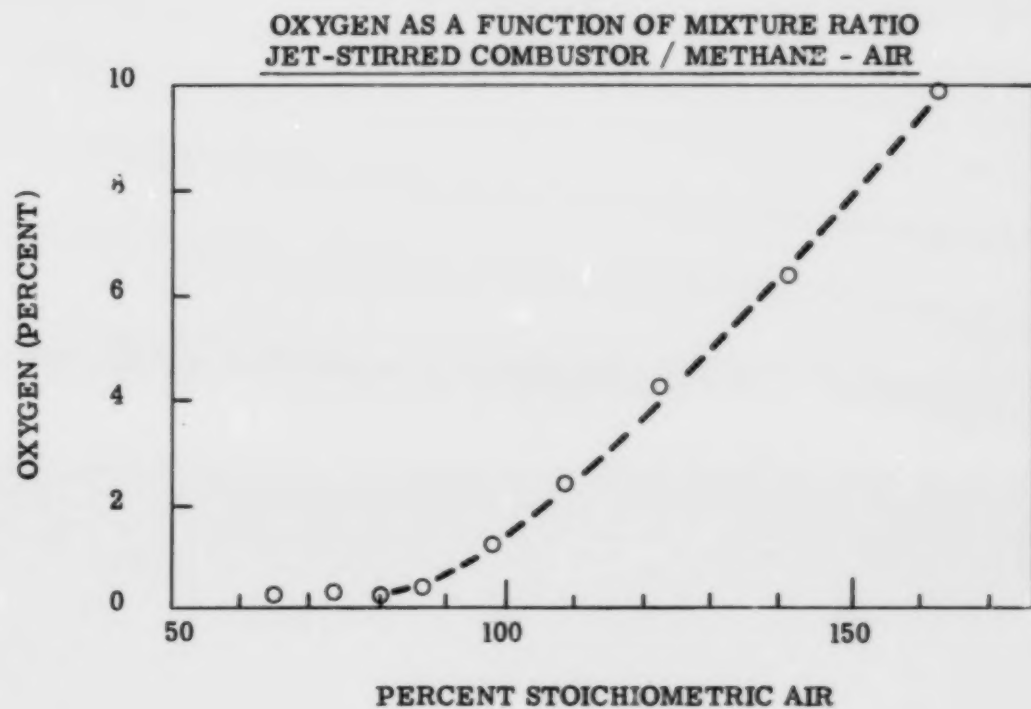


FIGURE 2-6

EFFECT OF WATER-COOLED SAMPLING PROBE POSITION
ON JET-STIRRED COMBUSTOR TEMPERATURE

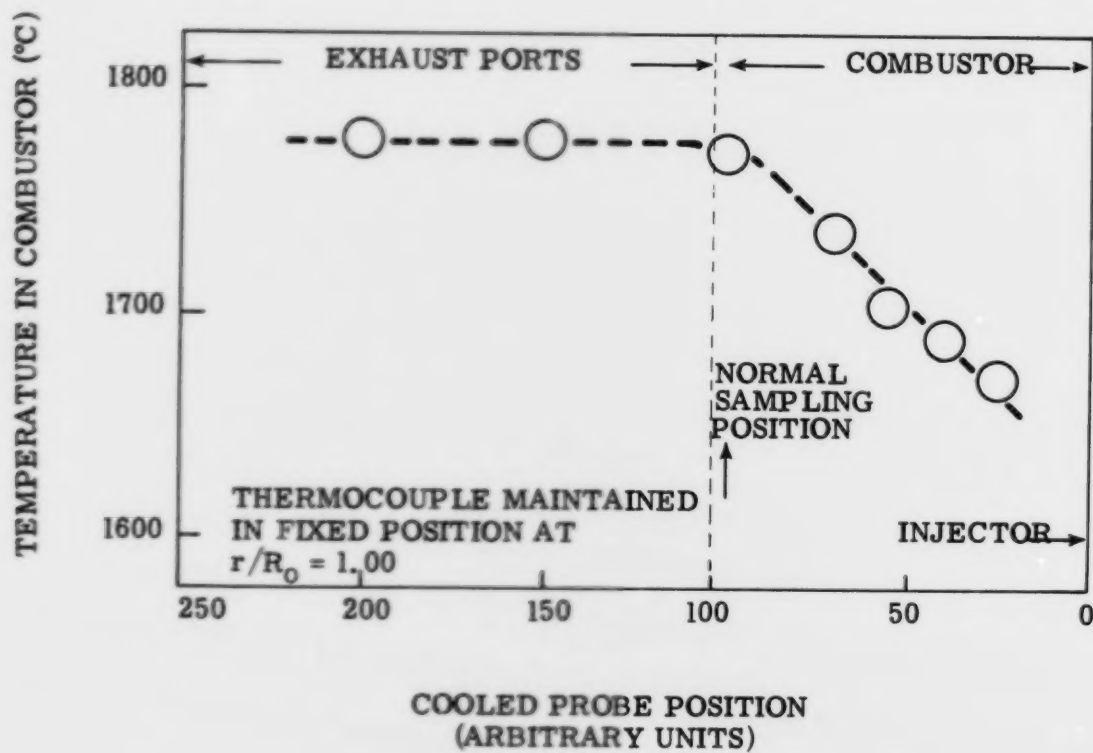


FIGURE 2-7

TEMPERATURE AS A FUNCTION OF MIXTURE RATIO
JET-STIRRED COMBUSTOR / CARBON MONOXIDE - AIR

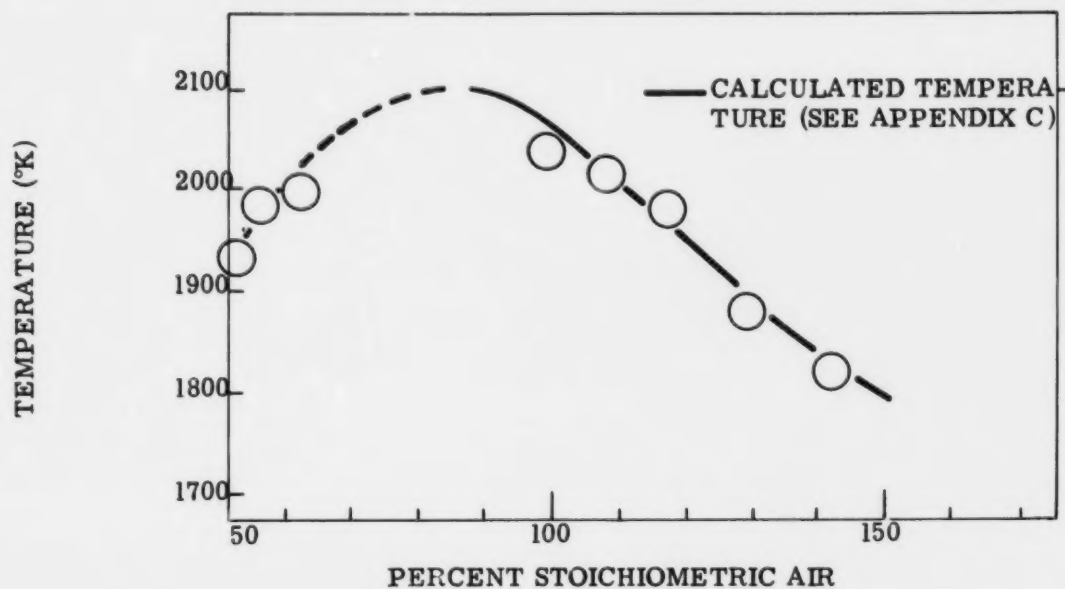


FIGURE 2-8

TEMPERATURE PROFILES IN JET-STIRRED AT
REPRESENTATIVE STOICHIOMETRIES COMBUSTOR / CARBON MONOXIDE - AIR

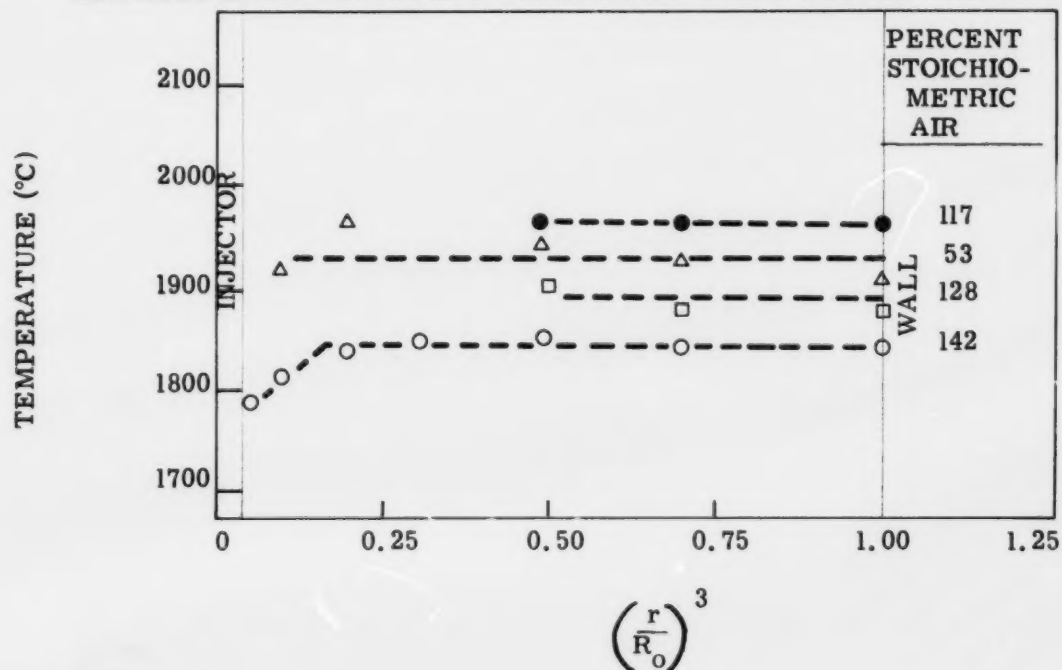


FIGURE 2-9

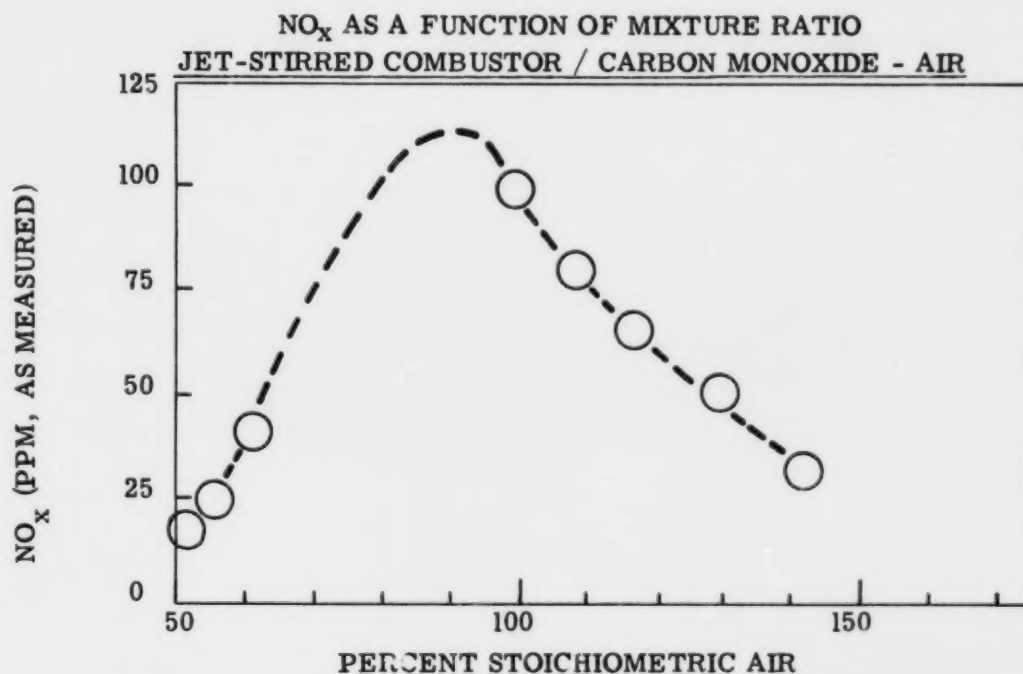
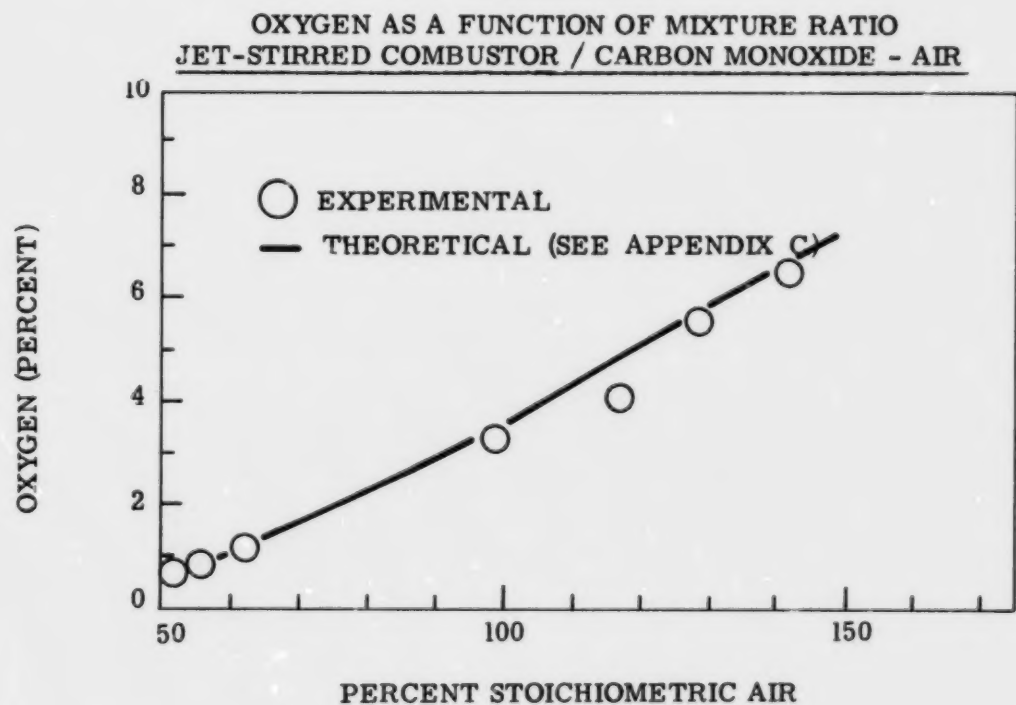


FIGURE 2-10



The oxygen concentration is shown in Figure 2-10 and is in good agreement with theoretical calculations indicated by the solid line.

Careful temperature probing of the reaction zone was accomplished and a study of the effect of preheat on NO_x formation was undertaken for propane. Data were also taken with hydrogen fuel for better characterization of the flame temperature vs. mixture ratio for this system in the jet-stirred combustor, and to obtain more accurate NO_x measurements under extremely lean and extremely rich conditions.

The NO_x measurements for the propane-air system are presented in Figure 2-11. The agreement with data taken previously is good in the case of no preheat. The NO_x peak appears to occur on the slightly fuel-rich size (at about 90% stoichiometric air).

The results for preheat in Figure 2-11 indicate only a slight effect on NO_x formation. However, temperature measurements show that only at 150% stoichiometric air conditions did the combustion temperature reflect fully the nominal amount of preheat. At 135% stoichiometric air the difference in combustion temperatures was only half of the preheat and there was no difference in combustion temperatures under fuel rich conditions. This lack of recovery of preheat temperature in the combustion zone is directionally consistent with adiabatic equilibrium calculations in which higher preheat causes dissociation at high temperatures and some of the sensible heat is converted to latent heat. At 150% stoichiometric air the difference of about 100°C in combustion temperature results in a NO_x increase by more than a factor of two. This behavior is in line with theoretical predictions of well-stirred reactor performance.

Temperature and oxygen measurements for the propane/air system are shown in Figure 2-12. The difference between theoretical adiabatic well-stirred reactor temperatures and experimentally increased temperatures indicates a heat loss on the order of 30-40 cal./sec. over the conditions studied. The measured oxygen concentrations match the calculated oxygen concentrations for a well-stirred reactor operating at the measured temperatures.

Probing of combustor temperature profiles showed that temperatures were quite uniform in the jet-stirred combustor for propane-air. The temperatures are plotted in Figure 2-13 against $(r/R_0)^3$. As discussed before, this parameter represents the fraction of total volume in a given zone of the combustor. The temperatures were found to be quite uniform throughout the combustor from the vicinity of the injector to within a short distance of the wall. Temperature probing was performed both with bare metal thermocouples and with thermocouples coated with silica. Because of the intense stirring and the apparent lack of catalytic effects on the thermocouples under the conditions studied, no difference was observed between the measurements obtained with coated and uncoated thermocouples.

Measurements were also made in the hydrogen-air system. The measurements were made under fuel-rich conditions around 40% stoichiometric air and under fuel lean conditions between 140% and 250% stoichiometric air. The chemiluminescence analyzer permits more accurate analysis of combustion gases at low NO_x levels than we were able to achieve during the previous investigation (2-3) which employed Envirometrics electrochemical analyzers.

FIGURE 2-11

NO_x FORMATION IN JET-STIRRED COMBUSTOR (PROPANE/AIR)

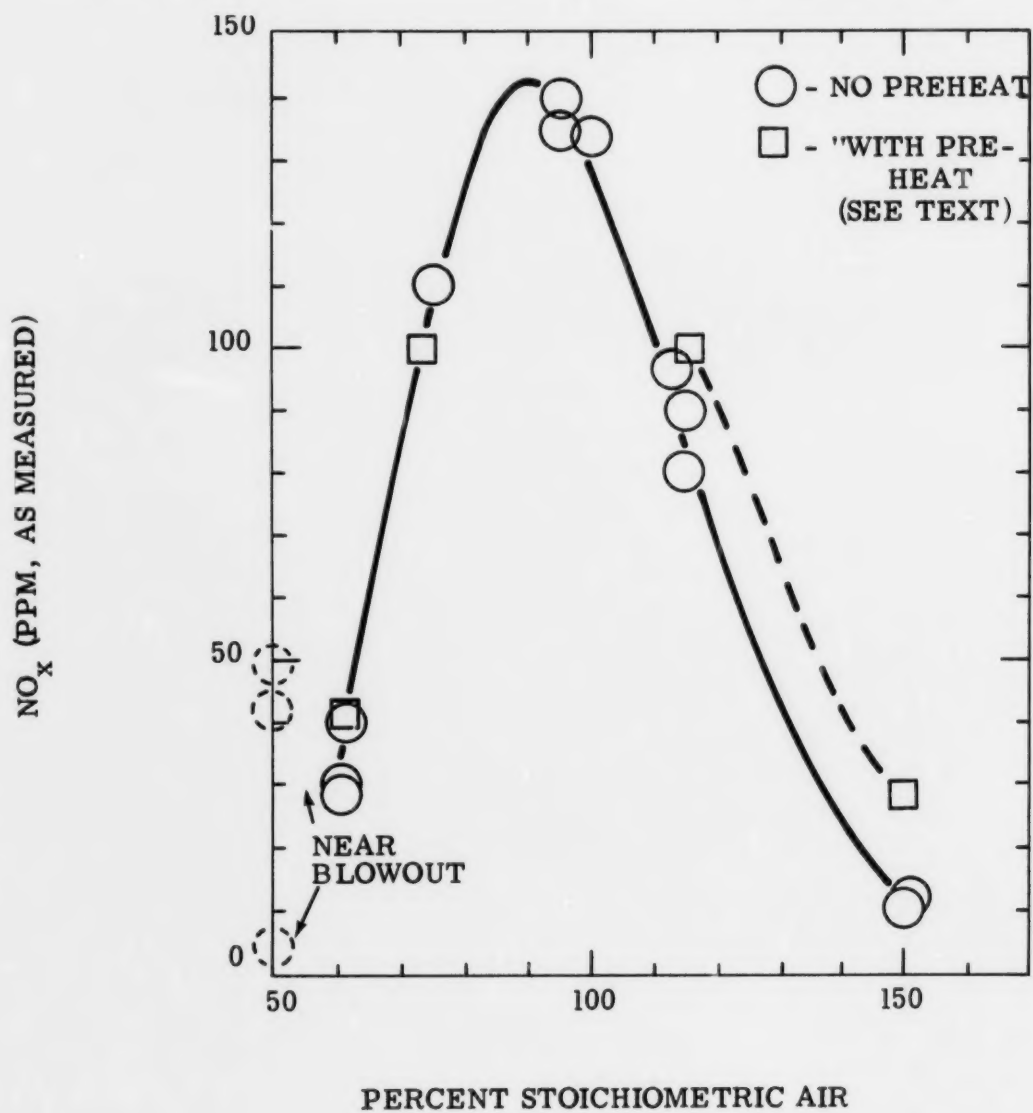


FIGURE 2-12

TEMPERATURE AND OXYGEN LEVELS
PROPANE - AIR

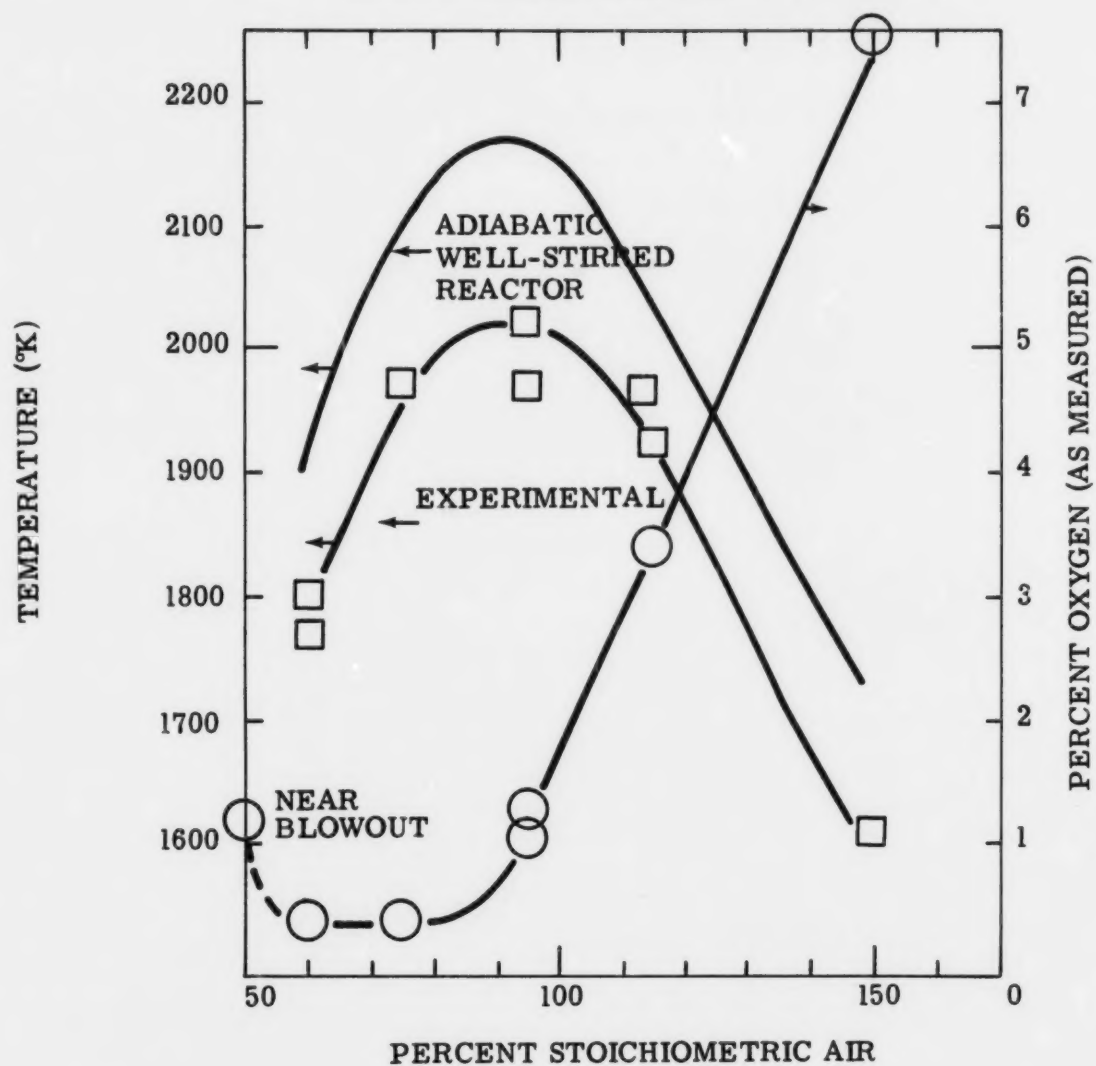
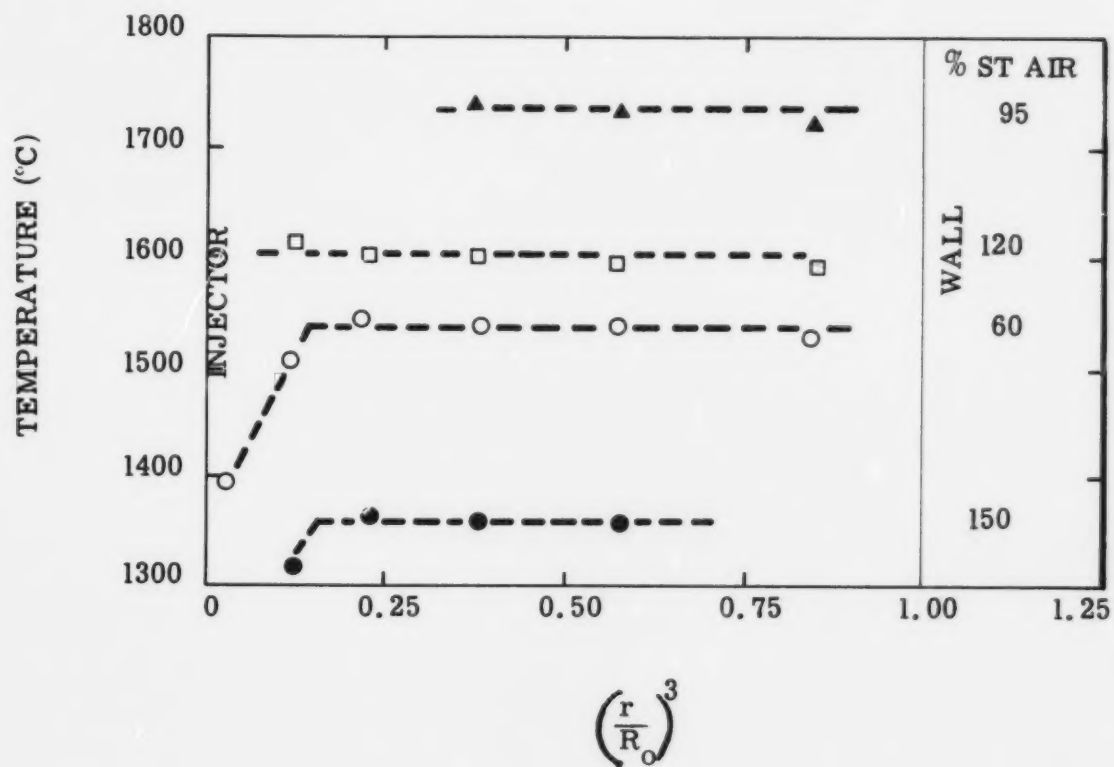


FIGURE 2-13

TEMPERATURE PROFILES IN JET-STIRRED COMBUSTOR
PROPANE - AIR



Calculations were performed to show that the jet-stirred combustor operates as a well-stirred reactor for "clean" combustion systems (hydrogen and carbon monoxide) and calculations have been performed on propane to test a quasi-global combustion model for calculations of NO_x formation. The results (2-4) of this study are reported in Appendix C. The calculations have been valuable to our current program to point out critical areas for experimentation and further kinetic studies. As discussed in detail in Appendix C, the theoretical analysis based on a simplified quasi-global approach failed to produce predicted NO_x concentrations in agreement with the experimental results for the propane/air system. This lack of agreement was particularly pronounced under fuel-rich conditions. Therefore, it was concluded that the investigation should be broadened to a detailed treatment of the kinetic data and also, that further experimental results should be obtained under conditions which eliminated heat loss as well as mixing limitations for comparison in theoretical predictions.

2.2 The Multiburner

Studies in the multiburner were undertaken to allow investigation of combustion reactions with well-controlled heat loss. The multiburner was operated as a flow reactor for this portion of this study with both hot and cold walls. The multiburner studies conducted indicated the need for the development of a new combustor capable of behavior as a well-stirred reactor under adiabatic conditions. These complementary studies with stirred reactors and flow reactors provide data on a range of conditions from well-mixed combustion controlled by chemical kinetics to diffusion flames controlled by fluid mechanics.

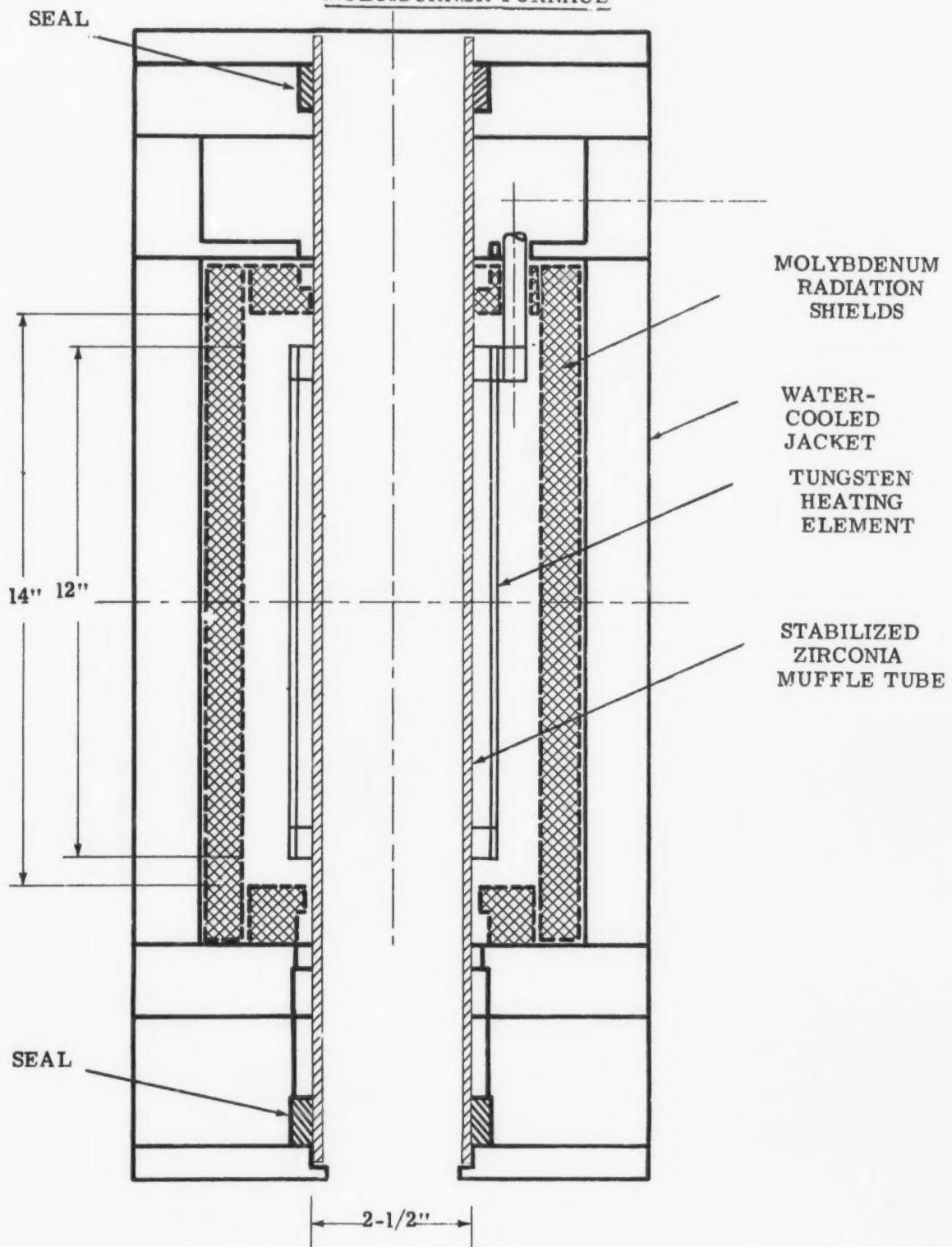
2.2.1 The Multiburner Furnace

The multiburner (so-called because it was designed to burn gas, oil or coal in the same idealized combustion zone) is an electrically-heated furnace with a zirconia muffle tube that is capable of attaining temperatures up to about 2500°K. The furnace is shown schematically in Figure 2-14. The furnace heating zone has tungsten mesh heating elements and molybdenum radiation shields and is purged with gettered argon to extend furnace component lifetimes. High temperature gasketing for the furnace is composed of zirconia felt. Temperatures inside the furnace are monitored with tungsten-rhenium thermocouples which also serve as the input to the temperature controller for the furnace when operating in the automatic mode. Wall temperatures can also be monitored by optical pyrometry through three sight ports provided in the side of the furnace. The power supply is a 25 KVA AC unit which is also equipped with a thermal watt converter for input to the controller in cases where it is desirable to control power input rather than strictly the temperature of the furnace. The controller on the power supply is also capable of operating in a "manual" mode, in which case current input to the furnace is controlled.

2-4 Engleman, V. S., Bartok, W., Longwell, J. P., and Edelman, R. B., Fourteenth Symposium (International) on Combustion, p. 755, The Combustion Institute, 1973.

FIGURE 2-14¹⁷

MULTIBURNER FURNACE



The muffle tube in the furnace has a heated length of 15 inches and the "constant temperature section" of the heated zone is uniform within $\pm 10^{\circ}\text{C}$ under combustion operation conditions. The muffle tube is quite stable at high temperatures and can be exposed to varying thermal environments in the temperature range above 1300°C . However, extreme care must be exercised in heating up and cooling down the furnace since the zirconia is most sensitive to thermal shock in the temperature range around 900°C .

The multiburner can be operated with the combustion zone wall temperature at any desired level and at the extremes it can either be used to add heat to the combustion zone or, if desired, to remove heat. Thus, the multiburner can operate with all of the flexibility of a laboratory combustor without the high heat loss generally found in small scale devices. This permits the use of the multiburner under combustion conditions that would not be possible with the typical small scale combustor.

2.2.2 Burner Design

The burners used in this part of the study were designed to be simple examples of the following types of burners:

- premixed flat flame
- premixed focused flame
- diffusion flame - with interchangeable fuel nozzles

The simple design of each of these burners (shown in Figures 2-15, 16 and 17) was aimed at ease of comparison with analytical calculations. Each of the burners was readily interchangeable with the others because they were all built into the same size water jacket, which served to maintain constant burner temperatures during combustion experiments. Even though the burners produced three different basic flame types, the total burner face area, through which combustion gases pass, was maintained constant for all three types.

The flat flame burner has a porous stainless steel disc across its face which provides a flat velocity profile for the combustion gases entering the furnace. The gases are mixed immediately before entering the burner body and pass through a pair of mixing/calming plates before exiting through the porous disc. A diagram of the flat flame burner is given in Figure 2-15.

The premixed focused flame burner used in this study is characteristic of a commercial gas furnace burner; the burner has a single center hole and eight pilot holes to stabilize the flame. As in the flat flame burner, the fuel and air are mixed immediately before entering the burner body and pass through mixing plates before exiting from the burner face. A diagram of the premixed focused flame is given in Figure 2-16.

FIGURE 2-15

FLAT FLAME BURNER

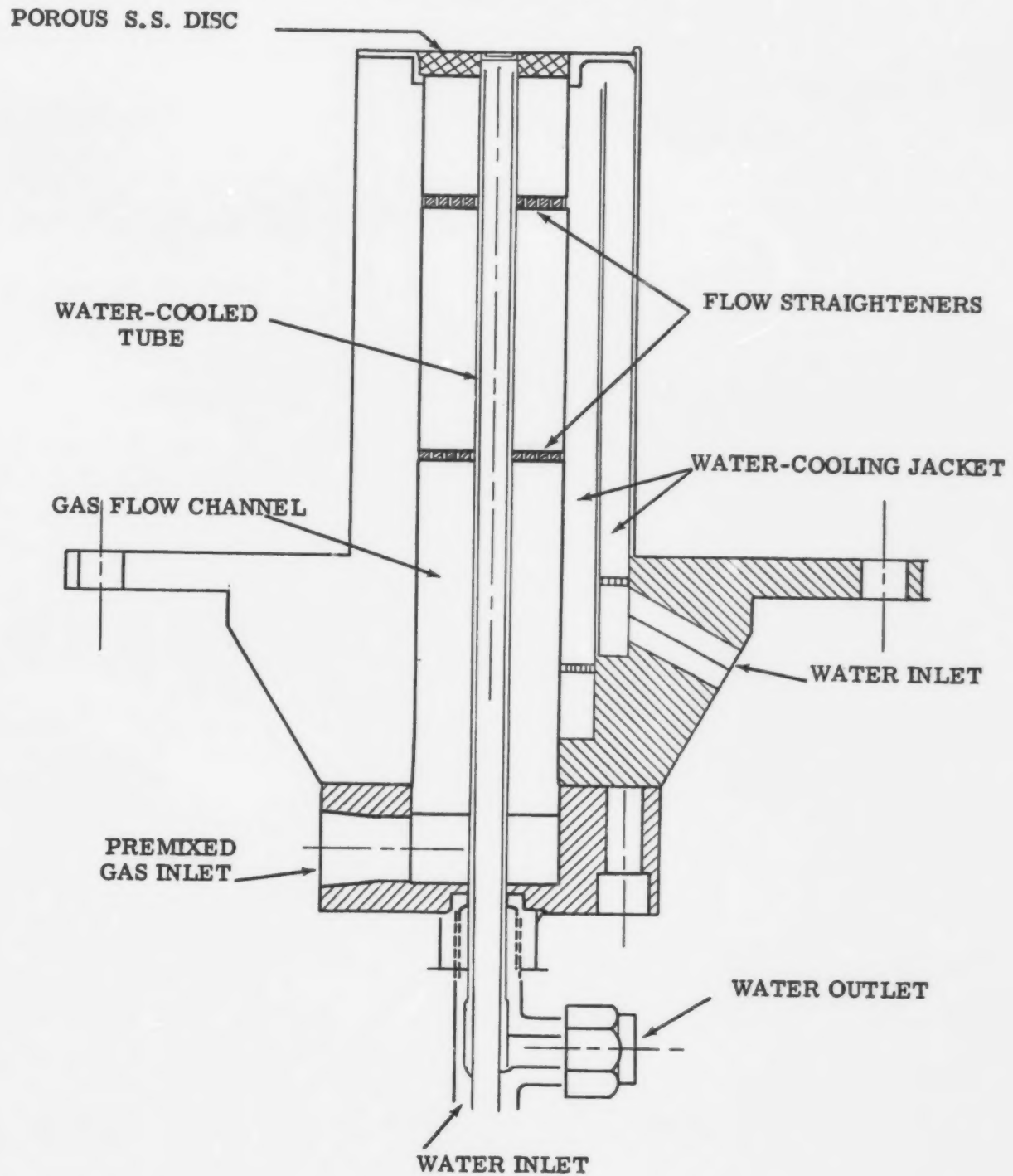


FIGURE 2-16

PREMIXED FOCUSED FLAME BURNER

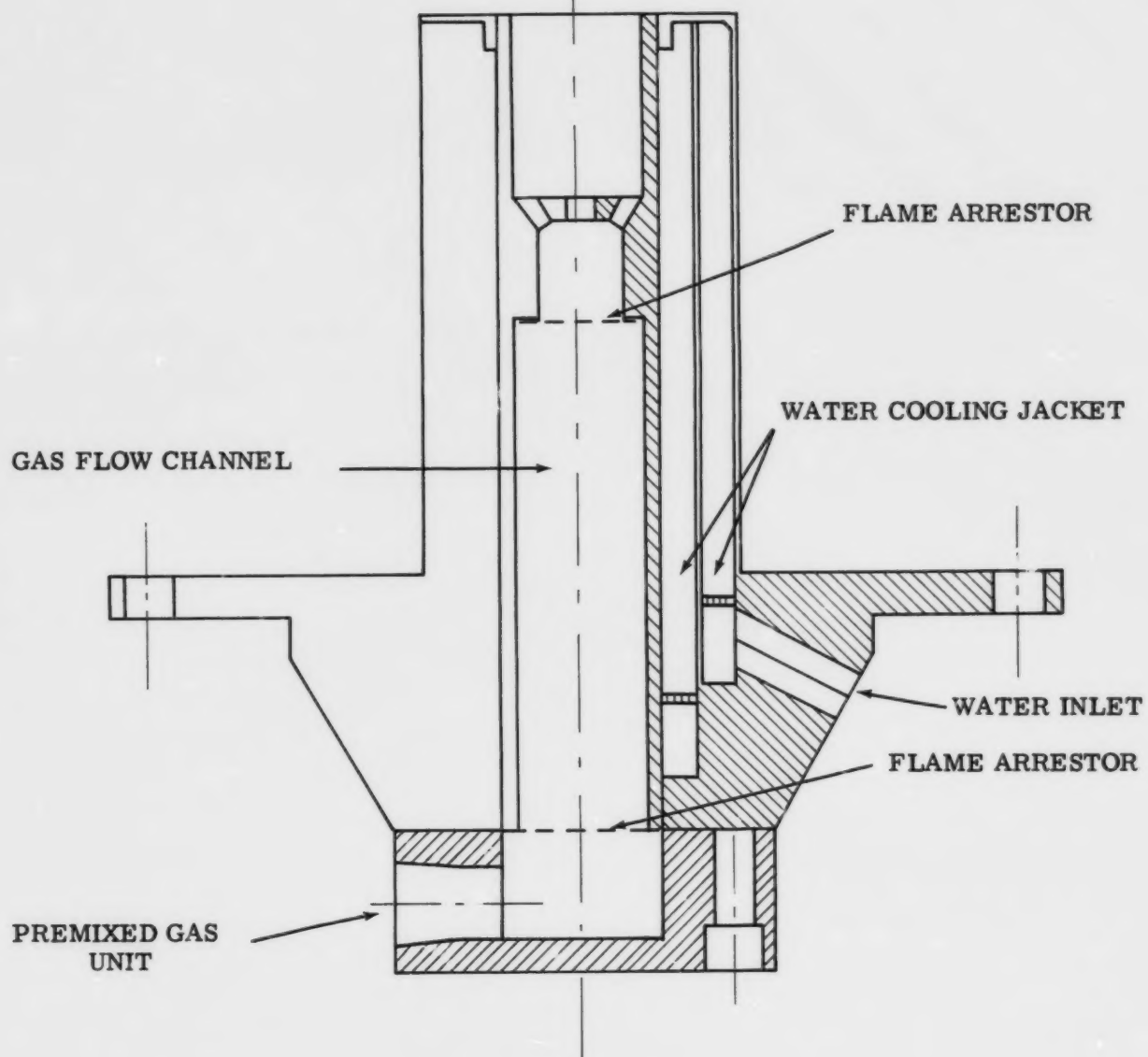
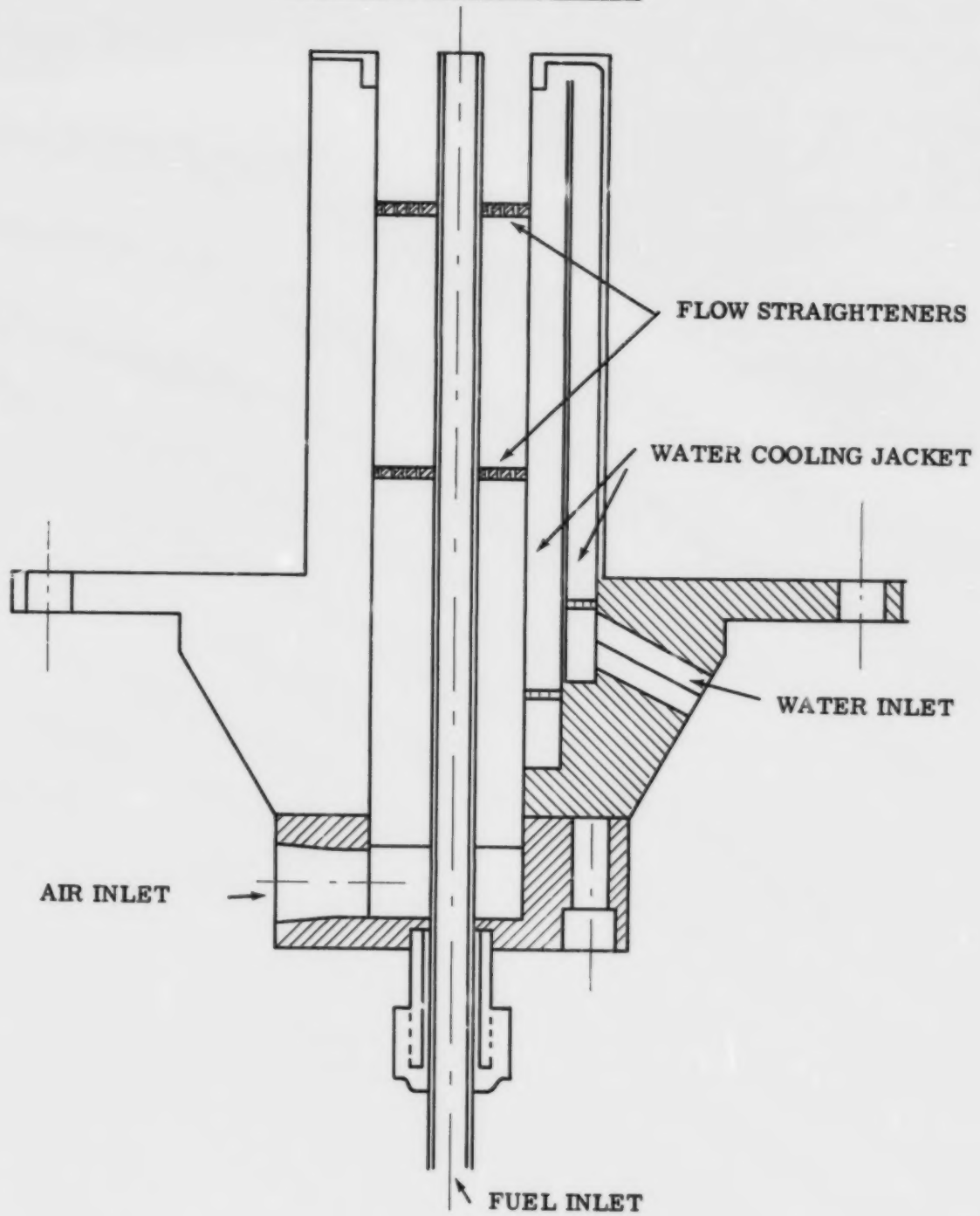


FIGURE 2-17

DIFFUSION FLAME BURNER



The diffusion flame burner is of the concentric type with the fuel flowing through the inner tube and the air flowing through the outer one. Two types of fuel injector were tested; one with a single fuel jet and the other with an orifice plate containing six 0.020 inch diameter holes covering the fuel jet to produce turbulence and increase mixing. The latter, called the "stabilized" diffusion burner was found to give better performance. The single fuel jet burner was tested in two different configurations; one in which the fuel jet diameter was kept constant when changing fuels from methane to propane allowing the velocities to change between the fuels, and one in which the fuel velocity was kept constant for the two fuels by changing the fuel jet diameter. A diagram of the diffusion flame burner is given in Figure 2-17.

2.2.3 Sampling and Gas Analysis

Combustion gas samples were extracted through a cooled quartz probe drawn to a nozzle tip. The sampling probe was cooled to 65°C to prevent water condensation in the probe. The Teflon sampling lines were also heated to prevent water condensation before the water knockout. The sample touched only quartz and Teflon lines until it was cooled sufficiently to prevent further reaction at which point stainless steel lines were used.

The combustion gases were analyzed for NO and NO_x with a Thermoelectron Model 10A Chemiluminescence analyzer. The analysis for NO is accomplished directly while the analysis for NO_x is accomplished by converting NO₂ (and under certain conditions other nitrogenous compounds) to NO and then analyzing for NO.

Analyses for CO and CO₂ were performed with two MSA 303 Analyzers, both of the NDIR type. Stacked cells each with a dual range switch allowed full scale ranges from 0.1% to 15% for CO and from 0.5% to 25% for CO₂.

Oxygen analysis was performed with a Beckman Model 742 polarographic oxygen analyzer with full scale ranges from 1% to 25%.

Hydrocarbon analyses were performed with a Beckman Model 400 flame ionization analyzer with full scale ranges calibrated from 50 ppm to 5% hydrocarbon as methane.

2.2.4 Data Reduction

Experimental data as taken were coded onto computer input forms and were reduced to measured species concentrations by a data reduction program. The data produced in this phase of the program are presented in the Appendix. A further subroutine can also be called to plot the results on a printer plot. The data plots are also found in the Appendix.

A summary of runs completed in this phase is presented as Table 2-1. The table is divided into three sections; section A covers the cold wall tests, section B the hot wall tests on premixed flames, and section C the hot wall tests on diffusion flames. For each of the runs in the table fuel type, burner type, firing rate, mixture ratio, and type of probing are given. Wall temperature is shown for the hot wall tests. The experimental findings on premixed flames are discussed in Section 2.2.5 and the findings on diffusion flames are discussed in Section 2.2.6.

TABLE 2-1
SUMMARY OF RUNS MADE WITH MULTIBURNER (PHASE I)

A. Cold Wall Tests ^a						
Run No.	Fuel Type	Burner Type	Firing Rate SCFM Air	Mixture Ratio % Stoich Air	Probing*	
101	Propane	Flat Flame	0.854	83 98 120 101 106 103 122 94 83 101 101 120 120 107 128 145 86 104 96 115 76 119 80 110 132 88 101	I/O I/O I/O AX AX/RD AX/RD AX/RD AX/RD AX/RD AX/RD AX/RD RD AX/RD	

* I/O = Input/Output
AX = Axial
RD = Radial

** Stabilized Diffusion
*** High Velocity Flame (Lifted)

TABLE 2-1 (CONTINUED)
SUMMARY OF RUNS MADE WITH MULTIBURNER (PHASE I)

B. Hot Wall Tests - Premixed Flames					Mixture Ratio % Stoich Air	Probing	Wall Temp. °C
Run No.	Fuel Type	Burner Type	Firing Rate SCFM Air				
115	Methane	Flat Flame	0.481		161	RD	1703
					141	RD	1853
					60	RD	1783
117	Methane	Flat Flame	0.481		161	AX/RD	1703
					119	AX/RD	1703
					80	AX/RD	2098
118	Propane	Flat Flame	0.481		161	AX/RD	1723
					61	AX/RD	1838
120	Propane	Focused Flame	0.481		156	AX/RD	1768
121	Propane	Focused Flame	0.481		125	AX/RD	2068
					101	I/O	2068
					101	I/O	2138
					82	I/O	2138
					117	I/O	2068
					78	I/O	2068
					95	I/O	2068
					117	I/O	2138
					95	I/O	2138
					78	I/O	2138
					101	I/O	2138
130	Methane	Flat Flame	0.481		140	AX/RD	1858
131	Methane	Flat Flame	0.481		120	AX/RD	2043
					78	AX/RD	2043
					111	AX/RD	2138
					101	AX/RD	2218

TABLE 2-1 (CONTINUED)

SUMMARY OF RUNS MADE WITH MULTIBURNER (PHASE I)

B. Hot Wall Tests - Premixed Flames (cont'd)

Run No.	Fuel Type	Burner Type	Firing Rate SCFM Air	Mixture Ratio % Stoich Air	Probing	Wall Temp. °C
131(cont)	Methane	Flat Flame	0.481	111	I/O	2218
				120	I/O	2218
				131	I/O	2218
				140	I/O	2218
				151	I/O	2218
				91	I/O	2218
				80	I/O	2218
				160	AX/RD	1713
132	Methane	Focused Flame	0.481	160	AX/RD	1713
133	Methane	Focused Flame	2.094	140	AX/RD	1863
134	Methane	Focused Flame	0.481	140	AX/RD	1858
				65	AX/RD	1873
135	Propane	Focused Flame	0.481	139	AX/RD	1898
136	Propane	Focused Flame	2.094	141	AX/RD	1883
137	Propane	Focused Flame	2.094	121	AX/RD	2068
138	Propane	Focused Flame	0.481	121	AX/RD	2068
139	Methane	Focused Flame	0.481	120	AX/RD	2043
140	Methane	Focused Flame	2.094	120	AX/RD	2048

TABLE 2-1 (CONTINUED)
SUMMARY OF RUNS MADE WITH MULTIBURNER (PHASE I)

C. Hot Wall Tests - Diffusion Flames				Firing Rate SCFM Air	Mixture Ratio % Stoich Air	Probing	Wall Temp. °C
Run No.	Fuel Type	Burner Type					
122	Methane	S. Diff		2.094	160	AX/RD	1723
123	Methane	S. Diff		2.094	140	AX/RD	1863
					120	AX/RD	2048
					80	AX/RD	2098
124	Methane	S. Diff		2.094	160	I/O	2228
					140	I/O	2228
					120	I/O	2228
					100	I/O	2228
					80	I/O	2228
					100	AX	2228
125	Propane	S. Diff		2.094	160	AX/RD	1698
126	Propane	S. Diff		2.094	141	AX/RD	1883
127	Propane	S. Diff		2.094	114	AX/RD	2143
					80	AX	2143
128	Methane	Large Single Hole		2.094	160	AX/RD	1713
129	Methane	S. Diff		2.094	140	AX/RD	1863
					140	RD	1863

2.2.5 Results for Premixed Flames

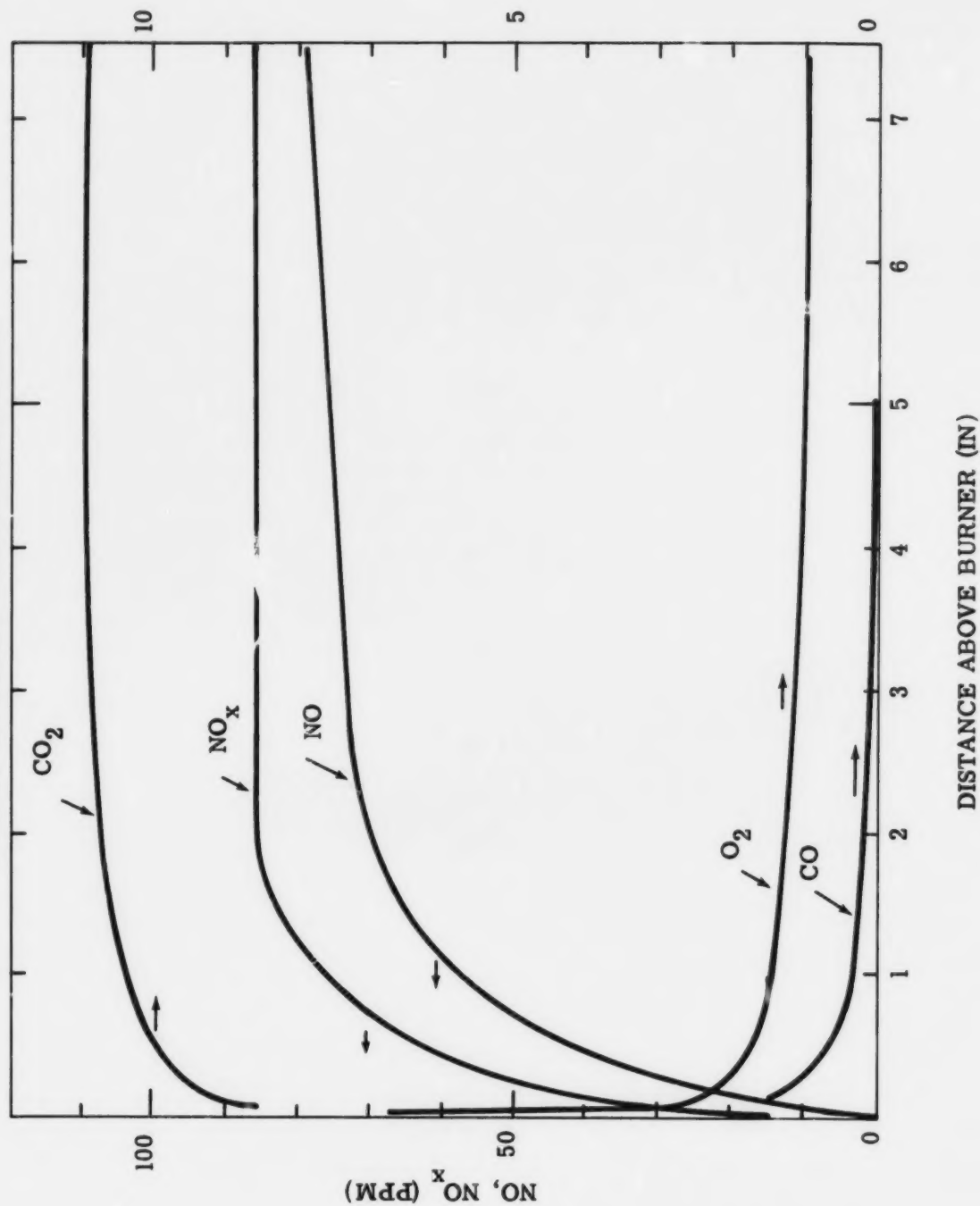
Species profiles have been obtained for premixed flames of methane-air and propane-air in the multiburner with hot and cold walls. Two types of premixed flames were studied: (1) the flat flame in which the flame zone is flat across the burner face and the flame is essentially one-dimensional, and (2) the shaped flame which is more representative of premixed furnace burners although much more complex than the flat flame in a fluid mechanical sense. The cold-wall runs are listed in Table 2-1(B). The data listings for these runs are presented in Appendix F. The NO_x plots for the individual runs are presented in Appendix D and the plots for $\text{CO}/\text{CO}_2/\text{HC}/\text{O}_2$ are presented in Appendix E. A summary of the types of data obtained on premixed flames will be presented in this section while the comparisons with theoretical calculations will be discussed in Section 3.

Centerline species profiles (CO , CO_2 , O_2 , NO and NO_x) for a premixed flat flame of methane/air at 104% stoichiometric air are presented in Figure 2-18. While the hydrocarbons are not plotted in this figure, about 20,000 ppm were measured within 0.05 inches of the burner face, but the concentration had dropped off to 70 ppm at 0.10 inches, and to essentially zero at 0.50 inches. The oxygen profile drops rapidly from about 7% within 0.05 inches to about 2.4% at 0.10 inches, and to 1.5% at 1 inch, settling at about 0.8% at greater distances. It was not possible to probe close enough to the burner face to permit observation of the increasing portion of the CO profile, but the decreasing portion is plotted from a distance of 0.1 inches outward with only minor concentrations of CO measurable after 5 inches. The CO_2 concentration increases rapidly, reaching 90% of its ultimate value within 0.5 inches of the burner face. The NO_x plot exhibits substantial curvature in the region up to about two inches from the burner face and increases only gradually thereafter.

It is interesting to note that the NO measurements are only about 2/3 of the NO_x measurements up to one inch and about 3/4 of the NO_x measurements up to two inches. At 10 inches the NO is about 90% of the NO_x . There are a number of possible interpretations for this early NO_2 peak.* One possible interpretation is that during the quenching process in the probe, a portion of the oxygen atoms combine with the NO to form NO_2 . Calculations indicate that, with instantaneous quenching to 300°K and assuming no heterogeneous reactions, 100 ppm of NO and 1,000 ppm of oxygen atoms react to form 38 ppm of NO_2 and 62 ppm of NO (allowing all possible reactions between species containing nitrogen and oxygen but ignoring species containing carbon or hydrogen). Such a calculation, while oversimplified by the idealized quenching and limitation of species, should still be somewhat conservative because of the probable underestimation of oxygen atom concentration in the flame zone.

* Cernansky, N. P., and Sawyer, R. F., "NO and NO_2 Formation in a Turbulent Hydrocarbon/Air Diffusion Flame", Fifteenth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, 1974; Merryman, E. L., and Levy, A., "Nitrogen Oxide Formation in Flames: The Roles of NO_2 and Fuel Nitrogen", Fifteenth Symposium; Fenimore, C. P., "Ratio of Nitrogen Dioxide to Nitric Oxide in Fuel-Lean Flames", Combustion & Flame, volume 1, page 85, 1975.

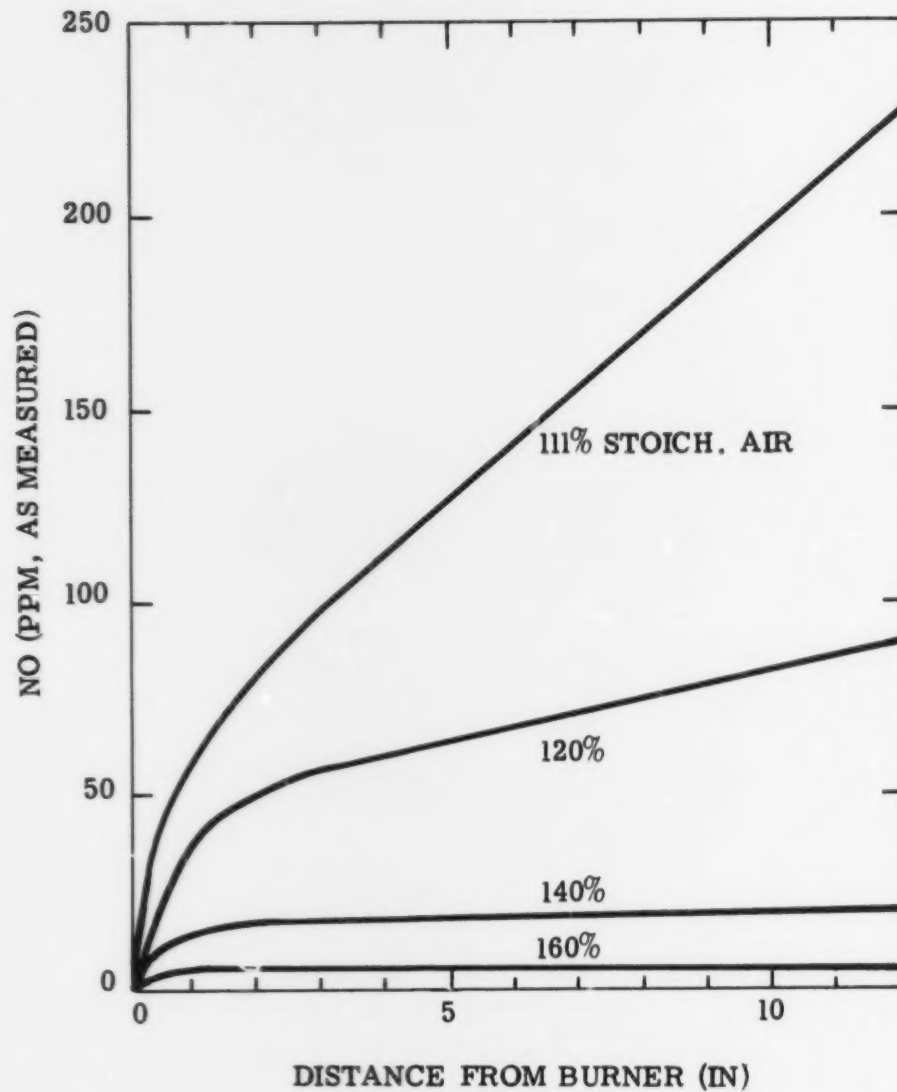
FIGURE 2-18
PREMIXED FLAT FLAME (METHANE / AIR)
104% STOICHIOMETRIC AIR



To give an idea of the results of NO probing at other stoichiometries, premixed flat flame data for methane/air are plotted in Figure 2-19. At each stoichiometry on this plot, curvature can be observed in the first inch or so from the burner face. As the stoichiometry changes from 111% stoichiometric air to 160% stoichiometric air, the temperature drop is sufficient to decrease post-flame NO_x formation despite increasing oxygen concentrations. This factor is accentuated by the unheated walls. At 104% stoichiometric air, NO_x is formed more rapidly near the burner face, but the concentration flattens out after about two inches so that the concentration at seven inches from the burner face is lower than that for 111% stoichiometric air. The combination of lower oxygen concentration in the post-flame zone and the temperature drop caused by heat losses result in this lower post-flame concentration.

FIGURE 2-19

PREMIXED FLAT FLAME (METHANE/AIR)



Heated walls change the post-flame picture, as would be expected. With the walls maintained at the adiabatic flame temperature at each stoichiometry, peak NO_x concentrations at 500 msec residence time are observed at 100% stoichiometric air as shown in Figure 2-20. NO_x concentrations appear to approach zero at about 70% and at 150% stoichiometric air when the walls are maintained adiabatic. However, if the walls are maintained at a constant temperature of 2220°K , only minor differences are noted on the fuel rich side (very little post-flame NO_x formation) while major differences appear under fuel lean conditions. Because of the substantial concentrations of oxygen present under fuel lean conditions, the high temperature encourages the formation of post-flame NO_x and rather than dropping off, the NO_x levels increase on the fuel lean side, approaching 2000 ppm at 150% stoichiometric air and 500 msec residence time. This indicates that if substantial air preheat were used, high NO_x levels would result on the fuel lean side. However, high preheat on the fuel rich side does not have the same effect in a premixed flame. With interstage heat removal to allow burnout at lower temperatures, after a fuel-rich first stage, the NO_x levels resulting from high-temperature, high-oxygen operation would be avoided.

2.2.6 Results for Diffusion Flames

Limited data were taken with diffusion flames to investigate their behavior under a variety of heat loss conditions. Some investigations were also made into the effect of fuel jet velocity on NO_x formation.

The detailed data and centerline species plots are presented in the Appendix. Only illustrative highlights will be covered in this section. Under adiabatic wall conditions (wall temperature maintained at the adiabatic flame temperature) the NO concentrations as a function of stoichiometry are similar to those for premixed flames far downstream of the burner face. In Figure 2-21 it can be seen that methane/air exhibits a peak NO level of 1000 ppm at 100% stoichiometric air for 150 msec residence time for adiabatic wall condition. Adiabatic flame temperatures vary with stoichiometry. At 100% stoichiometric air, the adiabatic flame temperature is about 2220°K , while at 60% stoichiometric air it is 1784°K and at 160% stoichiometric air it is 1709°K for methane/air combustion. With the walls heated to 2220°K , the higher oxygen level at higher excess air causes more rapid post-flame NO formation at a constant temperature. For a residence time of 150 msec, peak NO_x is shifted from 100% stoichiometric air to 120% stoichiometric air when the walls are maintained at 2200°K . As the residence time is increased further towards the 500 msec residence time used with the flat flame (with walls at 2220°K), the peak would shift toward leaner mixtures, and the diffusion flame NO curve in Figure 2-21 would look more and more like the flat-flame NO curve in Figure 2-20.

A comparison between the NO_x levels for turbulent diffusion flames of methane/air and propane/air with adiabatic walls is illustrated in Figure 2-22. The NO_x levels for propane/air are somewhat higher which could be attributed in part to the higher adiabatic equilibrium temperature for propane/air and in part to differences in flame chemistry. The curves are similar in shape and behavior.

FIGURE 2-20
PREMIXED FLAT FLAME (METHANE/AIR)

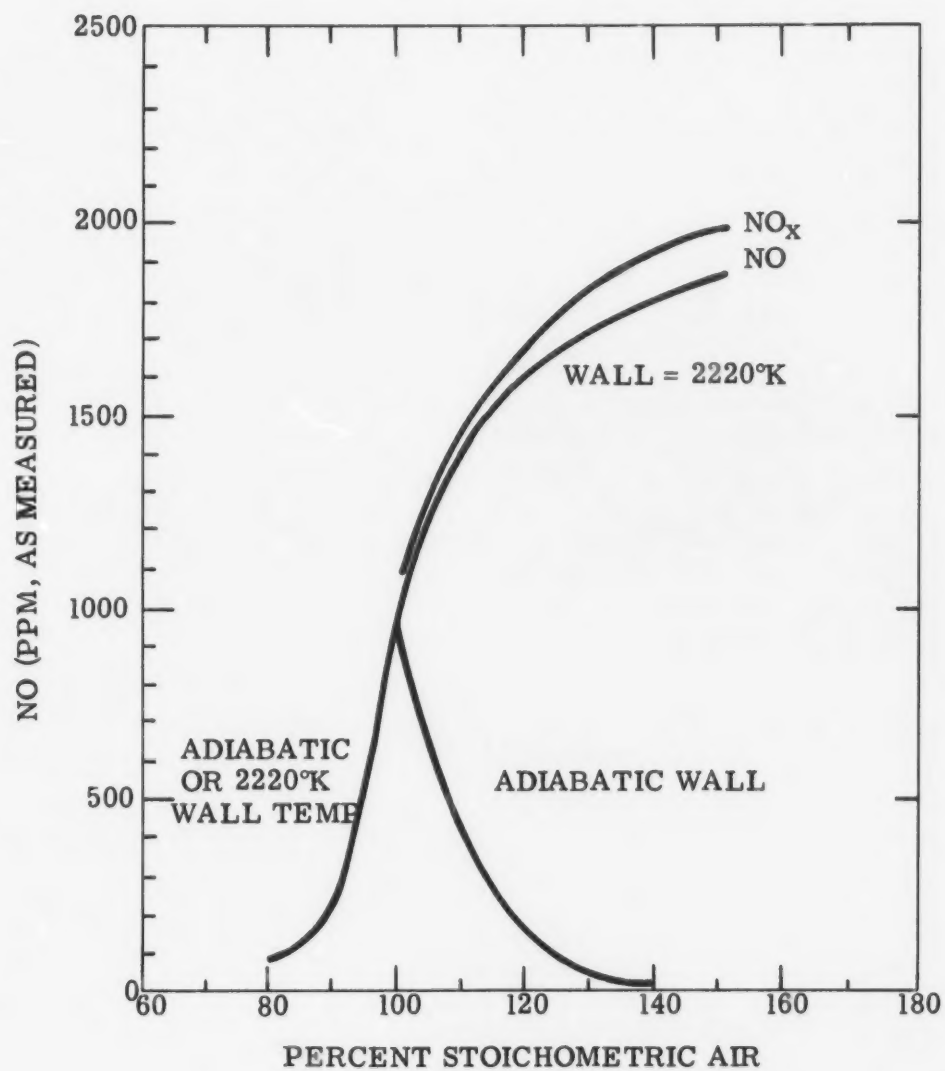


FIGURE 2-21

TURBULENT DIFFUSION FLAME (METHANE/AIR)

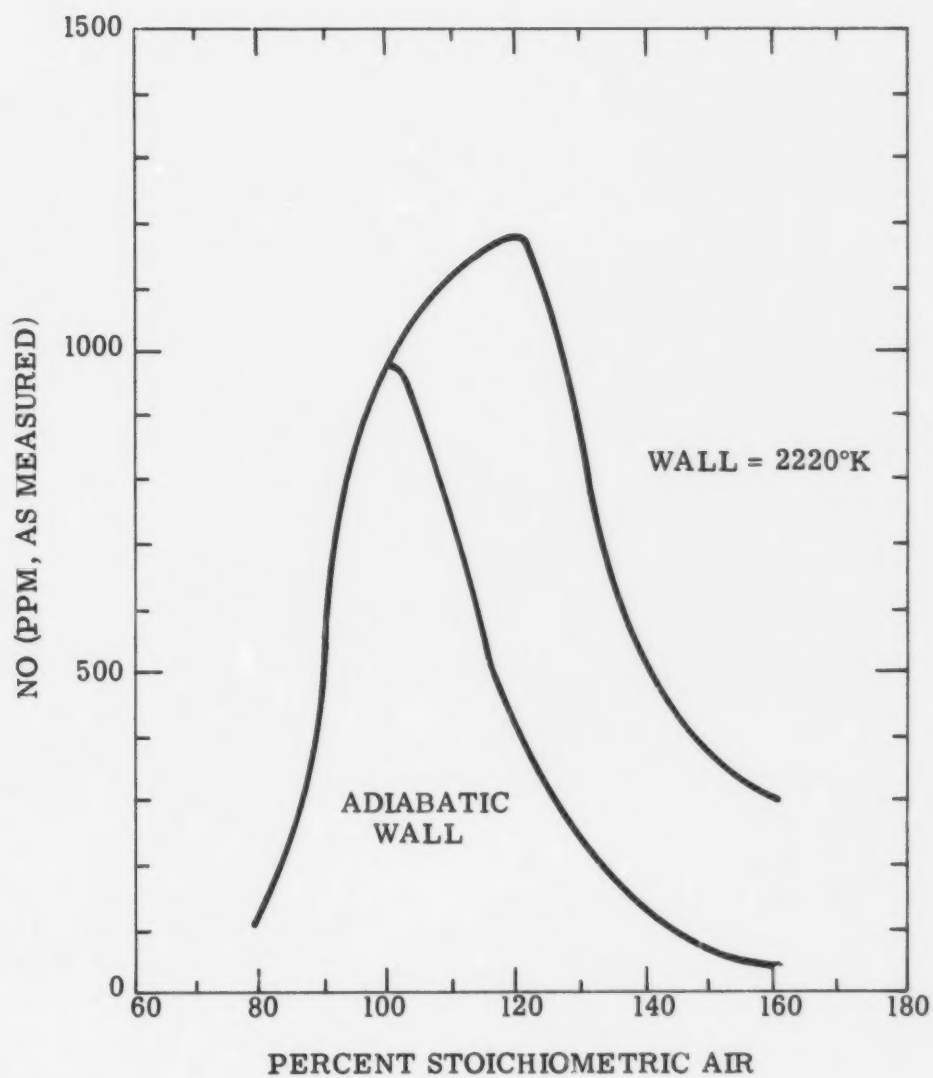
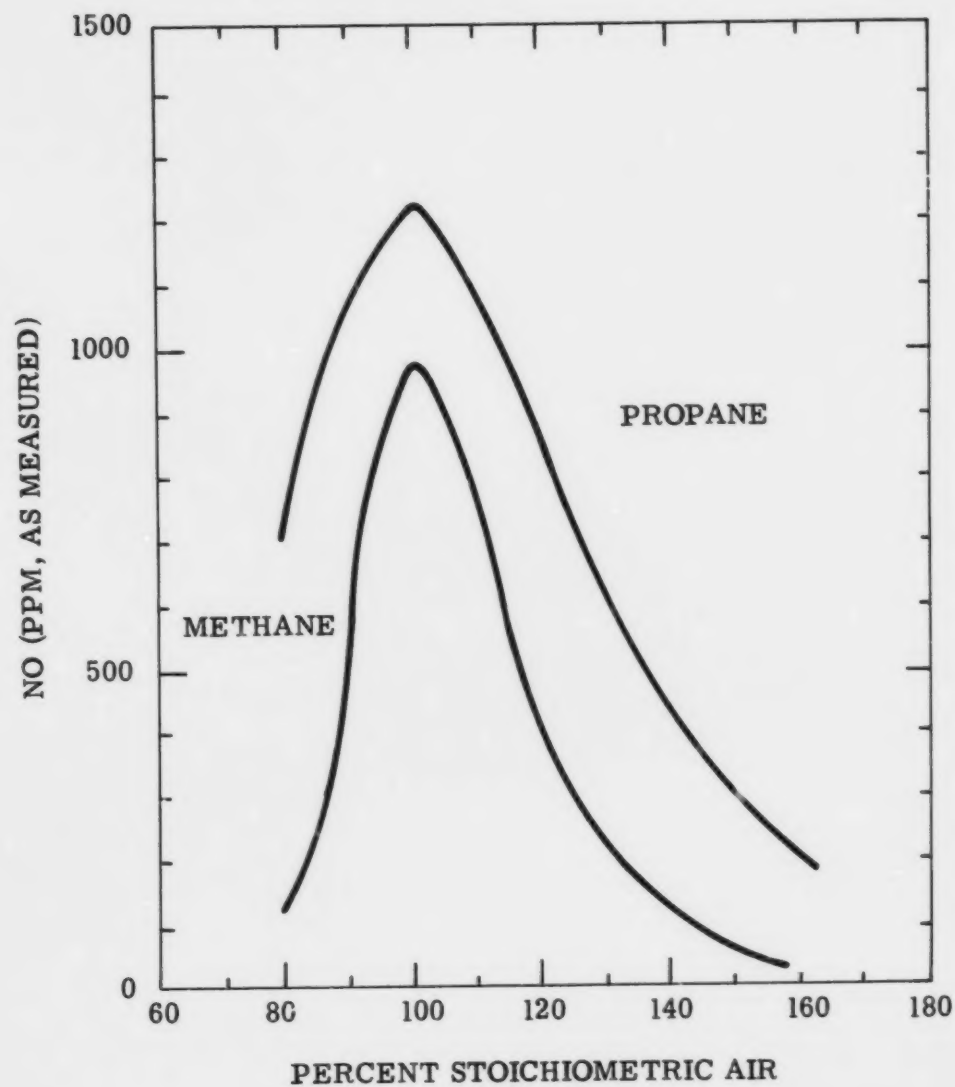


FIGURE 2-22
TURBULENT DIFFUSION FLAME



A comparison of results for different fuel jet velocity and induced turbulence yields some interesting results. Three types of fuel jets were used in the same basic burner. All fuel jets had strictly axial injection with no induced swirl. The fuel jet of the stabilized burner had a 0.250 inch inside diameter which was covered with an end-plate with six 0.020 inch holes drilled in a circular pattern. The fuel jet of the large single hole burner had a 0.250 inch inside diameter fuel jet with no end plate and the small single hole burner had 0.156 inch inside diameter fuel jet with no end plate. The latter two fuel jets were sized so that the velocity of the methane from the large jet matched the velocity of the propane from the small jet at the same stoichiometry.

Table 2-2 shows that for methane/air under excess air conditions the stabilized jet yields lower NO_x results than either the large single hole or small single hole burners and the results drop off more rapidly as the excess air level is increased. This is probably caused by the rapid breakup of the multiple individual jets, resulting in behavior similar to that found in a premixed flame. For the small single hole fuel nozzle the measured NO_x levels are essentially independent of excess air levels on an "as measured" basis. This behavior seems to indicate that the fuel jet from this burner maintains its integrity for a long distance downstream so that stoichiometry plays a smaller role in NO_x level.

Propane/air gives higher NO_x levels than methane/air for the stabilized jet and for the small single hole, as expected from the higher flame temperature. But the large single hole burner gives much lower NO_x levels than either of the other two burners. This fuel/jet combination gives the lowest jet velocity and may provide an explanation for the results since in this case, the fuel velocity is smaller than the air velocity. The low velocity fuel jet would cause lack of penetration of the fuel into the air stream and recirculation of the surrounding air jet to mix with the fuel stream near the burner face. This could cause locally fuel rich combustion to yield results similar to that of staged combustion. This subject was not pursued extensively at this time since the major objective of this study was the understanding of the chemistry rather than the fluid mechanics. However, it is noted as a possible area for future investigation.

TABLE 2-2
DIFFUSION FLAME NO/NO_x MEASUREMENTS

Burner	NO/NO _x , ppm					
	Methane			Propane		
	Percent Stoichiometric Air 120	130	140	Percent Stoichiometric Air 110	125	150
Stabilized (6 Hole)	30/35	16/18	5/10		55/60	25/30
Large Single Hole	40/45	25/30	15/20		35/37	10/15
Small	45/55	45/50	40/45	68	60/65	48/50

Measurements taken after 100 msec residence time.

Velocity of methane from large single hole burner matches velocity of propane small single hole burner at same stoichiometry. Air velocity constant.

3. THEORETICAL CALCULATIONS

Theoretical calculations have been undertaken to obtain comparisons between experimental data obtained under well-defined conditions and detailed chemical kinetics calculations. In addition, consideration has been given to the significance of chemical reactions for which data are available and the potential significance of reactions for which data are not available. This section contains a discussion of the thermochemical and kinetic calculations that have been performed thus far.

3.1 Equilibrium Calculations on Premixed Flames

Equilibrium calculations have been performed using the NASA CEC71 computer program with the thermochemical information from the JANAF Thermochemical Tables, Second edition (NSRDS-NBS 37). Equilibrium compositions for the adiabatic flame temperature at one atmosphere for fuel/air compositions with initial conditions of 298°K at one atmosphere have been calculated for methane/air, propane/air, hydrogen/air, and carbon monoxide/air. The information is presented in Tables 3-1 through 3-4. Only species for which concentrations exceeded 5 ppm are included in the tables; species considered in the calculations that did not exceed 5 ppm are listed at the bottom of the table. Input air is considered to be dry and to contain appropriate percentages of argon and carbon dioxide.

3.2 Survey of Coupled NO_x/Combustion Kinetics

A survey of kinetic data for methane/air combustion was initiated during this phase of the study. The status of the study at the end of this phase is described below. An updated version of the survey will be found in Reference 3-1.

The 25 species considered along with those species eliminated from primary consideration are listed in Table 3-5 along with the factors that went into making the species selections. The reactions included in this portion of the study were those involving the 25 primary species for which experimental or theoretical information was available in the literature. A prescreening of the literature indicated that such information existed for 142 reactions. Thus, these reactions were numbered from 1 to 142* on an interim basis. During the detailed reaction data accumulation it was determined that there was not sufficient information in the literature to yield a numerical estimate for some of these reactions (although the information on some of them was sufficient to ascertain that the rates were slow). It was also decided not to maintain separate headings for unimolecular reactions of differing order. Thus, numerical data were available only on 127 of the 142 reactions of the interim list.

3-1 Engleman, V. S., Survey and Evaluation of Kinetic Data on Reactions in Methane/Air Combustion, EPA-600/2-76-003, January, 1976.

* This interim numbering differs from the final numbering system in Reference 3-1 which runs from 1 to 322. A cross-reference will be found in Appendix A.

TABLE 3-1
EQUILIBRIUM COMPOSITION OF PRODUCTS IN METHANE/AIR COMBUSTION

P=1 ATM
INITIAL TEMP. = 298°K

PCT STOICH AIR	60	80	100	120	140	160
TEMP, DEG K	1784	2097	2226	2045	1861	1709
PRODUCTS	PRODUCT MOLE FRACTIONS					
AR	0.00709	0.00787	0.00837	0.00856	0.00867	0.00875
CO	0.09824	0.05328	0.00898	0.00086	0.00011	0.00002
CO2	0.03488	0.05757	0.08541	0.07955	0.06969	0.06165
H	0.00011	0.00057	0.00039	0.00004	0.00000	0.00000
H2	0.11459	0.03529	0.00364	0.00037	0.00006	0.00001
H2O	0.15114	0.18548	0.18296	0.15890	0.13859	0.12261
NO	0.00000	0.00006	0.00197	0.00333	0.00264	0.00183
NO2	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
N2	0.59395	0.65948	0.70061	0.71569	0.72502	0.73195
O	0.00000	0.00000	0.00021	0.00016	0.00005	0.00001
OH	0.00001	0.00036	0.00286	0.00197	0.00082	0.00033
O2	0.00000	0.00001	0.00459	0.03057	0.05434	0.07285

MOLE FRACTION LESS THAN 0.000005

C(S)	C	CH	CH2	CH2O	CH3	CH4	CN	CN2	C2
C2H	C2H2	C2H4	C2N	C2N2	C2O	C3	C3O2	C4	C5
HCM	HCO	HNO	HO2	H2O(S)	H2O(L)	H2O2	N	NH	NH2
NH3	N2C	N2H4	N2O	N2O4					

TABLE 3-2
EQUILIBRIUM COMPOSITION OF PRODUCTS IN PROPANE/AIR COMBUSTION

P=1 ATM
INITIAL TEMP. = 298°K

PCT STOICH AIR	60	80	100	120	140	160
TEMP DEG K	1822	2140	2254	2076	1888	1732
PRODUCTS	PRODUCT MOLE FRACTIONS					
AR	0.00728	0.00805	0.00852	0.00870	0.00879	0.00886
CO	0.12308	0.06366	0.01183	0.00132	0.00017	0.00003
CO2	0.04098	0.07233	0.10341	0.09667	0.08471	0.07484
H	0.00013	0.00065	0.00042	0.00005	0.00001	0.00000
H2	0.09554	0.02699	0.00316	0.00037	0.00037	0.00001
H2O	0.12281	0.15342	0.14841	0.12285	0.11232	0.09926
NO	0.00000	0.00010	0.00232	0.00366	0.00291	0.00201
NO2	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
N2	0.61016	0.67431	0.71307	0.72702	0.73510	0.74096
O	0.00000	0.00001	0.00028	0.00020	0.00006	0.00002
OH	0.00001	0.00047	0.00301	0.00205	0.00086	0.00034
O2	0.00000	0.00002	0.00555	0.03111	0.05501	0.07367

MOLE FRACTION LESS THAN 0.000005

C(S)	C	CH	CH2	CH2O	CH3	CH4	CN	CN2	C2
C2H	C2H2	C2H4	C2N	C2N2	C2O	C3	C3O2	C4	C5
HCN	HCO	HNO	HO2	H2O(S)	H2O(L)	H2O2	N	NH	NH2
NH3	N2C	N2H4	N2O	N2O4					

TABLE 3-3
EQUILIBRIUM COMPOSITION OF PRODUCTS IN HYDROGEN/AIR COMBUSTION

P=1 ATM
INITIAL TEMP. = 298°K

PCT STOICH AIR	60	80	100	120	140	160
TEMP, DEG K	2183	2349	2383	2216	2037	1884
PRODUCTS	PRODUCT MOLE FRACTIONS					
AR	0.00625	0.00707	0.00762	0.00792	0.00810	0.00824
CO	0.00016	0.00013	0.00005	0.00001	0.00000	0.00000
CO2	0.00005	0.00009	0.00019	0.00024	0.00026	0.00026
H	0.00219	0.00349	0.00181	0.00029	0.00004	0.00001
H2	0.1866	0.07954	0.01534	0.00223	0.00044	0.00010
H2O	0.28061	0.31478	0.32991	0.29115	0.25801	0.23054
NO	0.00004	0.00038	0.00260	0.00453	0.00404	0.00308
NO2	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
N2	0.52359	0.59194	0.63717	0.66067	0.67651	0.68872
O	0.00000	0.00007	0.00055	0.00049	0.00020	0.00007
OH	0.00045	0.00239	0.00687	0.00539	0.00272	0.00127
O2	0.00000	0.00012	0.00483	0.02707	0.04957	0.06770

MOLE FRACTIONS LESS THAN 0.000005

C(S)	C	CH	CH2	CH3	CH4	CN	CN2	CO
C2	C2H	C2H2	C2H4	C2N	C2O	C3	C302	C4
C5	HCN	HCO	HNO	H2O(S)	H2O(L)	H2O2	N	NH
NH2	NH3	N2C	N2H4	N2O	N2O4			

TABLE 3-4

EQUILIBRIUM COMPOSITION OF PRODUCTS IN CARBON MONOXIDE/AIR COMBUSTION

P=1 ATM

INITIAL TEMP. = 298°K

PCT STOICH AIR	60	80	100	120	140	160
TEMP, DEG K	2306	2417	2384	2285	2151	2009
PRODUCTS	PRODUCT MOLE FRACTIONS					
AR	0.00626	0.00704	0.00754	0.00787	0.00809	0.00824
CO	0.18884	0.09379	0.04226	0.01582	0.00472	0.00124
CO2	0.28016	0.30186	0.29690	0.27914	0.25497	0.23023
NO	0.00052	0.00292	0.00511	0.00589	0.00545	0.00442
NO2	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
N2	0.52382	0.58815	0.62909	0.65637	0.67485	0.68785
O	0.00009	0.00070	0.00106	0.00083	0.00044	0.00018
O2	0.00031	0.00555	0.01804	0.03407	0.05148	0.06785

MOLE FRACTION LESS THAN 0.000005

C(S) C CN CN2 C2 C2N C2N2 C2O C3 C3O2
C4 C5 N N2C N2O N2O4

TABLE 3-5

SPECIES CONSIDERED FOR KINETICS SURVEY ON METHANE/AIR COMBUSTION

SPECIES	PRIMARY	SECONDARY	LOG K AT 2000	FACTORS INCLUDED IN CONSIDERATION
C		X	-10	possible role in soot formation
CH	X	X	-10	hydrocarbon radical
CHN	X	X	-2	possible role in prompt NO
CHO	X	X	+3	stable radical
CH ₂	X	X	-8	hydrocarbon radical
CH ₂ O	X	X	+1	combustion intermediate
CH ₃	X	X	-5	hydrocarbon radical
CH ₃ O	X	X		possible role in ignition
CH ₄	X	X	-3	starting material
CN	X	X	-6	possible role in prompt NO
CNO		X		possible role in NO/HC interaction
CO	X	X	+7	combustion product
CO ₂	X	X	+10	combustion product
C ₂		X	-12	possible role in soot formation
C ₂ H		X	-6	C ₂ intermediates possibly important for fuel rich combustion of methane or higher hydrocarbons
C ₂ H ₂		X	-3	
C ₂ H ₃		X		
C ₂ H ₄		X	-5	
C ₂ H ₅		X		
C ₂ H ₆		X		
C ₂ O			-1	difficult to form from CO
C ₃			-10	possible role in soot formation more likely from higher hydrocarbons
C ₄			-15	
C ₅			-14	

TABLE 3-5 (CONTINUED)

SPECIES	PRIMARY	SECONDARY	LOG K AT 2000K	FACTORS INCLUDED IN CONSIDERATION
H	X	X	-3	combustion intermediate
HN	X	X	-8	possible role in prompt NO
HNO	X	X	-5	possible role in prompt NO
HO	X	X	0	combustion intermediate
HO ₂	X	X	-3	combustion intermediate
H ₂	X	X	0	combustion product
H ₂ N		X	-6	possible intermediate
H ₂ N ₂			-12	not likely for methane/air
H ₂ O	X	X	+4	combustion product
H ₂ O ₂		X		possible role in ignition
H ₃ N		X	-5	possible role fuel rich
H ₃ N ₂				not likely for methane/air
H ₄ N ₂			-14	not likely for methane/air
N	X	X	-9	important role NO formation
NO	X	X	-2	of prime interest
NO ₂	X	X	-4	oxidation of NO
NO ₃		X	-10	higher oxidation state of NO
N ₂	X	X	0	starting material
N ₂ O	X	X	-6	possible role in prompt NO
N ₂ O ₄			-15	not likely for methane/air
N ₂ O ₅			-18	not likely for methane/air
O	X	X	-3	combustion intermediate
O ₂	X	X	0	starting material
O ₃		X	-7	possible role in ignition

The interim recommended rates for the reactions used in this portion of the study are included here as Table 3-6. More up-to-date recommendations will be found in Reference 3-1. All reactions included in the table are covered by rate constants and/or comments. The rates are also calculated for temperatures of 300°, 1500°, and 2500°K in the direction indicated (F for forward and R for reverse). Where five asterisks appear in the comments section, only limited estimates are available and should be regarded with caution. It should be realized that recommended rates are evolutionary. As further kinetic and thermochemical data become available, recommendations require updating. Thus, any recommended rates should be considered as subject to further evaluation.

Additional reactions can be written involving these species in unimolecular and bimolecular reactions, some of which could prove to be significant in the mechanism of methane combustion with pollutant formation. Thus, a listing has been made of all the possible unimolecular and bimolecular reactions among 25 species in the methane/air combustion system. The listing (Appendix A) contains notations indicating the type of reaction for those included in the survey. An evaluation of the potential importance of each of these reactions in methane combustion will be found in Reference 3-1. The 322 reactions in this "master list" are numbered both with their interim reaction numbers, where applicable, and sequentially, with "X" numbers which cross-reference this list to the complete survey in Reference 3-1.

3.3 Kinetics Calculations

Kinetics calculations during this phase of the program were performed using the version of the CKAP* program modified for use on an IBM 370 computer. Difficulties were encountered in attempting to prevent negative concentrations in plug-flow cases. The rate of disappearance of hydrocarbons is so rapid as their concentrations approach zero that concentrations of these substances frequently go negative instead of leveling off near zero. By taking special care with step size control and relative error criterion, the problem could be alleviated in most cases.

The initial set of calculations for reaction screening and data comparisons have been run under isothermal conditions at the adiabatic flame temperature in the region between 80 and 120% stoichiometric air at atmospheric pressure. The isothermal approach offers a number of advantages: computer time is shortened, screening is facilitated since the rate parameters are held constant, and ignition is easily accomplished. Additional runs have been made for the case of adiabatic ignition.** These runs indicate the same qualitative behavior as the isothermal runs and basically similar proportions of reaction intermediates are computed, even though the absolute concentrations are not identical for the two cases.

* Supplied by EPA for use in this program. Developed for detailed kinetic analysis by Ultrasystems under EPA contract 68-02-0220.

** Such runs were accomplished by allowing a small amount of initial reaction to occur at high temperature. After a temperature rise of about 200°K, the system was dropped back to the lower temperature (initial temperature + temperature rise) and ignition was allowed to proceed.

TABLE 3-6

INTERIM RECOMMENDED RATES

RECOMMENDED RATES	REACTION	LOG A	B	C	COMMENTS	300	TEMP., KELVIN		
							1500	2000	2500
							LOG K		
1F.	CH + CHN = CH ₂ + CN	11.5	0.6	8.	***** NOTE B. BASED ON T1 (J-P)	7.2	12.2	12.6	12.8
2F.	CH + CHO = CH ₂ + CO	10.5	0.7	1.	***** NOTE B. BASED ON T1 (J-P)	11.5	12.6	12.7	12.8
3F.	CH + CH ₂ O = CH ₂ + CHO	11.0	0.7	4.	***** NOTE B. BASED ON T1 (J-P)	9.8	12.6	12.9	13.0
4F.	CH + CH ₃ = CH ₂ + CH ₂	11.1	0.7	5.	***** NOTE B. BASED ON T1 (J-P)	9.2	12.6	12.9	13.0
5F.	CH + CH ₄ = CH ₂ + CH ₃	11.4	0.7	6.	***** NOTE B. BASED ON T1 (J-P)	8.8	12.7	13.1	13.3
6F.	CH + CO ₂ = CH ₂ + CO	10.0	0.5	6.	***** NOTE A. BASED ON T1 (EST)	6.9	10.7	11.0	11.2
7F.	CH + H = CH ₂	11.7	0.5	0.	BASED ON T1 (EST) USE THIRD ORDER SEE 8F.	12.9	13.3	13.4	13.4
8F.	CH + H + M = CH ₂ + M				NO DATA WILL ESTIMATE				
9R.	CH ₂ + N = CH + HN	11.8	0.67	40.5	***** NOTE A. BASED ON M8 (J-P)	-16.0	8.0	9.6	10.5
10F.	CH + HN = CN + H ₂				NO DATA PROBABLY SLOW 9R FASTER THAN 10F 31R FASTER THAN 10R				
11F.	CH + HNO = CH ₂ + NO	11.8	0.5	0.	***** NOTE A. BASED ON T1 (EST)	13.0	13.4	13.5	13.5

NOTE A - BEST ESTIMATE AVAILABLE, USE WITH CAUTION

NOTE B - ONLY ESTIMATE AVAILABLE, USE WITH CAUTION

NOTE C - LIMITED EXPERIMENTAL DATA AVAILABLE, USE WITH CAUTION

TABLE 3-6 (CONTINUED)

RECOMMENDED RATES	1500-2500K	9/30/73				
REACTION	LOG A	B	C	COMMENTS	300	TEMP., KELVIN 1500 2000 2500 LOG K
12F. CH + HO = CHO + H	11.7	0.5	10.	***** NOTE A. BASED ON T1 (EST)	5.7	11.8 12.3 12.5
13R. CH2 + O = CH + HO	11.3	0.7	26.	***** NOTE B. BASED ON M8 (J-P)	-5.9	9.7 10.8 11.4
14F. CH + HO = CO + H2	NO DATA PROBABLY SLOW 13R FASTER THAN 14F 14R UNFAVORABLE					
15F. CH + HO2 = CHO + HO	11.7	0.5	6.	***** NOTE A. BASED ON T1 (EST)	8.6	12.4 12.7 12.9
16F. CH + HO2 = CH2 + O2	10.0	0.5	15.	***** NOTE B. BASED ON T1 (EST)	0.3	9.4 10.0 10.4
17R. CH2 + H = CH + H2	11.5	0.7	26.	***** NOTE B. BASED ON M8, T1 (J-P)	-5.7	9.9 11.0 11.6
18R. CH2 + HO = CH + H2O	11.7	0.5	6.	***** NOTE A. BASED ON T1 (EST)	8.6	12.4 12.7 12.9
19F. CH + N = CN + H	NO DATA WILL ESTIMATE					
20F. CH + NO = CHO + N	NO DATA PROBABLY SLOW					
21F. CH + N2 = CHN + N	NO DATA SPIN FORBIDDEN					
22F. CH + O = CO + H	11.7	0.5	4.	***** NOTE A. BASED ON T1 (EST)	10.0	12.7 12.9 13.0
23F. CH + O + M = CHO + M	16.	-0.5	0.	***** NOTE A. BASED ON T1 (EST)	14.8	14.4 14.3 14.3

TABLE 3-6 (CONTINUED)

RECOMMENDED RATES		1500-2500K		9/30/73		TEMP., KELVIN	
REACTION	LOG A	B	C	COMMENTS	300	1500	2000
				LOG K			
24F. CH + O2 = CHO + O	11.7	0.5	6.	***** NOTE A. BASED ON T1 (EST)	8.6	12.4	12.7
25F. CH + O2 = CO + HO				NO DATA PROBABLY SLOW			12.9
26R. CN + H + M = CHN + M	16.5	-0.5	0.	***** NOTE A. BASED ON T1 (EST)	15.3	14.9	14.8
27R. CH2O + CN = CHN + CHO	11.1	0.7	3.	***** NOTE A. BASED ON T1 (J-P)	10.6	12.9	13.1
28R. CH3 + CN = CHN + CH2	11.0	0.7	3.	***** NOTE A. BASED ON T1 (J-P)	10.5	12.8	13.0
29R. CH4 + CN = CHN + CH3	11.5	0.7	5.	***** BASED ON T1 (J-P) XPT 100X J-P 300K REQUIRE A=13.5 OR REQUIRE E=0.	9.6	13.0	13.3
30R. CHO + CN = CHN + CO	11.3	0.5	0.	***** NOTE A. BASED ON T1 (EST)	12.5	12.9	13.0
31F. CHN + H = CN + H2	11.4	0.7	18.	***** NOTE B. BASED ON T1 (J-P)	0.0	11.0	11.7
32F. CHN + HO = CN + H2O	11.3	0.6	5.	***** NOTE A. BASED ON T1 (J-P)	9.1	12.5	12.7
33R. CN + HN = CHN + N	11.0	0.5	2.	***** NOTE A. BASED ON T1 (EST)	10.8	12.3	12.4
34R. CN + HNO = CHN + NO	11.6	0.5	0.	***** NOTE A. BASED ON T1 (EST)	12.8	13.2	13.3
							12.5
							13.4
							12.2
							12.9
							12.5
							13.3

TABLE 3-6 (CONTINUED)

RECOMMENDED RATES	REACTION	LOG A	B	C	1500-2500K	9/30/73	COMMENTS	300	TEMP., KELVIN	
									1500	2500
									LOG K	
35F.	CHN + O = CN + HO	11.5	0.7	17.	**** BASED ON T1 (J-P)		NOTE B.	0.8	11.2	12.4
36F.	CHO + M = CO + H + M	20.4	-1.5	16.8	SRI ESTIMATE 4/11/73 BASED ON HINSHELWOOD -LINDEMANN THEORY XPTL REF B65 GIVES A=12.3, B=0.5, E=29. NOT SENSITIVE XPT			4.4	13.2	13.8
37F.	CHO + CHO = CH2O + CO	11.2	0.5	0.	**** BASED ON T1 (EST)		NOTE A.	12.4	12.8	12.9
38F.	CHO + CH2 = CH3 + CO	10.5	0.7	1.	**** BASED ON T1 (J-P)		NOTE A.	11.5	12.6	12.7
39F.	CHO + CH3 = CH2 + CH2O	11.2	0.7	4.	**** BASED ON T1 (J-P)		NOTE B.	10.0	12.8	13.1
40F.	CHO + CH3 = CH4 + CO	11.5	0.5	0.	**** BASED ON T1 (EST)		NOTE A.	12.7	13.1	13.2
41F.	CHO + CH4 = CH2O + CH3	11.9	0.6	9.	**** BASED ON T1 (J-P)		NOTE B.	6.8	12.5	12.9
42R.	CH2 + O = CHO + H	11.7	0.5	4.	**** BASED ON T1 (EST)		NOTE A.	10.0	12.7	12.9
43R.	CH2O + M = CHO + H + M	33.9	-4.5	87.	SRI ESTIMATE 4/11/73 BASED ON HINSHELWOOD -LINDEMANN THEORY			-40.6	6.9	9.5
44F.	CHO + H = CO + H2	10.5	1.	0.	SRI ESTIMATE 4/6/73 REF T1 ESTIMATES A=12.2, B=0.5, E=0.			13.0	13.7	13.8
										13.9

TABLE 3-6 (CONTINUED)

RECOMMENDED RATES	1500-2500K		9/30/73		300	TEMP., KELVIN	
	REACTION	LOG A	B	C		1500	2000
						LOG K	
45F.	CHO + NO = CH ₂ O + NO	11.5	0.5	0.	12.7	13.1	13.2
				***** NOTE A. BASED ON T1 (EST)			13.2
46R.	CH ₂ O + O = CHO + HO	11.3	1.	4.4	10.6	13.8	14.3
				BASED ON D22,N7,M27 USING B = 1 FIT MODIF ARRHENIUS D22 BEST HI T N7 & M27 BEST LO T			
47F.	CHO + HO = CO + H ₂ O	10.5	1.	0.	13.0	13.7	13.8
				SRI ESTIMATE 4/6/73 XPT 14. AT 2000K OTHER ESTS 12.5 AT 2000K			13.9
48R.	CH ₂ O + H = CHO + H ₂	10.1	1.	3.2	10.2	12.8	13.1
				BASED ON W32 USING B = 1 NO DATA ABOVE 1000K			13.2
49R.	CH ₂ O + HO = CHO + H ₂ O	9.5	1.	1.	11.2	12.5	12.7
				SRI ESTIMATE 4/6/73 AGREES WITH REF T1			12.8
50F.	CHO + N = CO + HN	11.3	0.5	2.	11.1	12.6	12.7
				***** NOTE A. BASED ON T1 (EST)			12.8
51F.	CHO + NO = CO + HNO	11.3	0.5	2.	11.1	12.6	12.7
				***** NOTE A. BASED ON T1 (EST)			12.8
52F.	CHO + O = CO + HO	11.5	1.	0.5	13.6	14.6	14.7
				SRI ESTIMATE 3/28/73 OTHER ESTS 12.8			14.9
53F.	CH ₂ + CH ₄ = CH ₃ + CH ₃	12.1	0.7	20.	-0.7	11.4	12.2
				***** NOTE A. BASED ON T1 (J-P)			12.7
54F.	CH ₂ + HNO = CH ₃ + NO	11.8	0.5	0.	13.0	13.4	13.5
				***** NOTE A. BASED ON T1 (EST)			13.5

TABLE 3-6 (CONTINUED)

RECOMMENDED RATES	1500-2500K		9/30/73		TEMP, KELVIN	
	REACTION	LOG A	B	C	LOG K	
55F. CH ₂ + HO = CH ₃ + O		11.7	0.5	6.	8.6	2500
				***** BASED ON T1 (EST)	12.4	12.9
56R. CH ₃ + H = CH ₂ + H ₂		11.3	0.7	3.	10.8	13.4
				***** BASED ON T1 (J-P)	13.1	
57R. CH ₃ + HO = CH ₂ + H ₂ O		10.8	0.7	2.	11.1	13.0
				***** BASED ON T1 (J-P)	12.7	
58F. CH ₂ + O ₂ = CH ₂ O + O		11.7	0.5	7.	7.8	12.8
				***** BASED ON T1 (EST)	12.3	
59R. CH ₃ + O = CH ₂ O + H		12.3	0.5	-0.3	13.8	14.0
				BASED ON M25, D22 USING B = 0.5 M25 LO T, D22 HI T	13.9	
991R. CH ₃ O + M = CH ₂ O + H + M		40.6	-7.5	22.6	5.6	13.1
				SRI ESTIMATE 4/11/73 BASED ON HINSHELWOOD -LINDEMANN THEORY NOTE A.	13.5	
60R. CH ₃ + O ₂ = CH ₂ O + HO		13.5	0.	30.	-8.4	10.9
				BASED ON D22 SRI RECOMMENDS C = 30 D22 GIVES C=10 FOUR CENTER	9.1	
61R. CH ₄ + M = CH ₃ + H + M		15.	0.	104.	-60.8	5.9
				BASED ON H32 FIRST ORDER	-0.2	
		17.3	0.	87.5	-46.4	9.7
				BASED ON H32 SECOND ORDER RECENT XPT	4.6	
62F. CH ₃ + HNO = CH ₄ + NO		11.7	0.5	0.	12.9	13.4
				***** BASED ON T1 (EST)	13.3	

TABLE 3-6 (CONTINUED)

RECOMMENDED RATES		1500-2500K		9/30/73		TEMP., KELVIN			
REACTION	LOG A	B	C	COMMENTS	300	1500	2000	2500	
				LOG K					
63R. CH ₄ + O = CH ₃ + HO	10.	1.	8.	BASED ON W25+H25 USING B = 1.	6.6	12.0	12.4	12.7	
64F. CH ₃ + HO ₂ = CH ₄ + O ₂	11.0	0.5	6.	***** NOTE A. BASED ON T1 (EST)	7.9	11.7	12.0	12.2	
65R. CH ₄ + H = CH ₃ + H ₂	10.7	1.	10.	BASED ON W30 USING B = 1. AGREES W/ OTHER XPT AND EVAL	5.9	12.4	12.9	13.2	
66R. CH ₄ + HO = CH ₃ + H ₂ O	13.5	0.	5.	BASED ON W31 EVAL 300-2000K AGREES G18, 300-500K	9.9	12.8	13.0	13.1	
992F. CH ₃ + O ₂ = CH ₃ O + O	9.4	1.	28.5	SRI ESTIMATE 4/11/73 BASED ON EARLIER EST USING B = 1.	-8.9	8.4	9.6	10.3	
67F. CN + NO = CO + N ₂	11.5	0.	0.	***** NOTE C. BASED ON B78 (XPT)	11.5	11.5	11.5	11.5	
993F. CN + O = CO + N	12.	0.	0.	BASED ON B78, R5 ASSUME C = 0 DATA 300-700K	12.0	12.0	12.0	12.0	
68F. CN + O ₂ = CO + NO	11.5	0.	0.	***** NOTE C. BASED ON B86 (XPT) UPPER LIMIT	11.5	11.5	11.5	11.5	
69F. CO + HNO = CO ₂ + HN	11.0	0.5	7.	***** NOTE A. BASED ON T1 (EST)	7.1	11.6	11.9	12.1	
70F. CO + HO = CO ₂ + H	9.6	0.5	0.	BASED ON TRANS STATE PARAMETERS H = -1, S = -30, CP = -3 LOG K = 11. AT 300K BETTER FIT TO DATA WITH A=5.9, B=2., C=-1	10.8	11.2	11.3	11.3	

TABLE 3-6 (CONTINUED)

RECOMMENDED RATES	1500-2500K		9/30/73		TEMP, KELVIN	
	REACTION	LOG A	B	C	300	1500 2000 2500 LOG K
71F. CO + H ₂ O = CO ₂ + H ₂	11.	0.	10.5	SRI ESTIMATE 9/11/73 REF L11 RECOMMENDS A=12., B=0., C=16.5	3.4	9.5 9.9 10.1
72R. CO ₂ + H ₂ = CO + H ₂ O	9.0	0.5	15.	***** NOTE A. BASED ON T1 (EST)	-0.7	8.4 9.0 9.4
73R. CO ₂ + N = CO + NO	11.3	0.5	25.	BASED ON T1 WITH HIGHER C PROBABLY SLOW SPIN FORBIDDEN	-5.7	9.2 10.2 10.8
74F. CO + NO ₂ = CO ₂ + NO	12.5	0.	30.	BASED ON B47, J6 LIMITED OLD DATA	-9.4	8.1 9.2 9.9
75F. CO + N ₂ O = CO ₂ + N ₂	11.0	0.	23.	***** NOTE C. BASED ON L9 (XPT)	-5.8	7.6 8.5 9.0
76R. CO ₂ = CO + O				USE THIRD BODY SEE 77R.		
77R. CO ₂ + M = CO + O + M	15.	0.	100.	BASED ON C26, O1 COMPLEX REACTION SLOW DISSOCIATION RECENT DATA	-57.9	0.4 4.1 6.3
78F. CO + O ₂ = CO ₂ + O	13.	0.	60.	BASED ON D22 MINIMUM E=50 HI T DATA FAIR AGRMT	-30.7	4.3 6.4 7.8
79R. H ₂ + M = H + H + M	14.3	0.	96.	BASED ON B88 M = AR BEST RECENT EVAL	-55.6	0.3 3.8 5.9
80F. H + HN = H ₂ + N	11.8	0.5	8.	SRI ESTIMATE OPR NO. 2, 2/15/73 BASED ON TRANS STATE PARAMETERS H = 7, S = -22, CP = -3	7.2	12.2 12.6 12.8

TABLE 3-6 (CONTINUED)

RECOMMENDED RATES	REACTION	1500-2500K			COMMENTS	300	TEMP., KELVIN		
		LOG A	B	C			1500	2000	2500
							LOG K		
81F.	$H + HNO = HN + HO$	11.3	0.5	13.	***** NOTE A. BASED ON T1 (EST)	3.1	11.0	11.5	11.9
82F.	$H + HNO = H2 + NO$	13.	0.	2.5	BASED ON H31 FIT DATA 200-2000K	11.2	12.6	12.7	12.8
83F.	$H + HO = H2 + O$	9.9	1.	7.	BASED ON B88 CRIT EVAL 400-2000K	7.3	12.1	12.4	12.7
84R.	$H2O + M = HO + H + M$	15.5	0.	105.	BASED ON B88 M = N2 CRIT EVAL 2000-6000K DIFFICULT TO STUDY	-61.0	0.2	4.0	6.3
85F.	$H + HO2 = HO + HO$	14.4	0.	1.9	BASED ON B88 CRIT EVAL 290-800K	13.0	14.1	14.2	14.2
86F.	$H + HO2 = H2 + O2$	13.4	0.	0.7	BASED ON B88 CRIT EVAL 290-800K	12.9	13.3	13.3	13.3
87F.	$H + HO2 = H2O + O$	13.0	0.	1.	BASED ON L11 EVAL 300-1000K LOWER THAN REC B88 12.9 AT 293K	12.3	12.9	12.9	12.9
88R.	$HO + H2 = H + H2O$	13.4	0.	5.2	BASED ON B88 EVAL, AGREES XPT	9.6	12.6	12.8	12.9
89F.	$H + N + M = HN + M$	16.5	-0.5	0.	***** NOTE A. BASED ON T1 (EST)	15.3	14.9	14.8	14.8
90R.	$HN + O = H + NO$	11.8	0.5	0.	SRI ESTIMATE QPR NO. 2, 2/15/73 BASED ON TRANS STATE PARAMETERS H = -1 S = -22, CP = -3	13.0	13.4	13.5	13.5

TABLE 3-6 (CONTINUED)

RECOMMENDED RATES		1500-2500K		9/30/73		TEMP, KELVIN			
REACTION		LOG A	B	C	COMMENTS	300	1500	2000	2500
91R. HO + N = H + NO		11.8	0.5	8.	SRI ESTIMATE QPR NO. 2, 2/15/73 BASED ON TRANS STATE PARAMETERS H = 7 S = -22, CP = -3 K = 13.5 AT 320K BASED ON REF C8 WOULD REQUIRE C = 0 ALSO USE C=0 FOR SCR GIVES 13.45 AT 2000K	7.2	12.2	12.6	12.8
92F. H + NO + M = HNO + M		16.3	0.	0.	BASED ON C20, H10 AT 300K USING B = 0, C = 0 M = H2 DATA 200-700K INDIC SLIGHT NEGATIVE E	16.3	16.3	16.3	16.3
93R. HNO + O = H + NO2		10.7	0.5	0.	***** NOTE A. BASED ON T1 (EST)	11.9	12.3	12.4	12.4
94F. H + NO2 = HO + NO		14.5	0.	1.5	RASED ON R90 300-600K NO DATA ON REVERSE	13.4	14.3	14.3	14.4
95R. HN + N = H + N2		11.8	0.5	0.	SRI ESTIMATE QPR NO. 2, 2/15/73 BASED ON TRANS STATE PARAMETERS H = -1 S = -22, CP = -3	13.0	13.4	13.5	13.5
96F. H + N2O = HN + NO		11.0	0.5	30.	***** NOTE A. BASED ON T1 (EST)	-9.6	8.2	9.4	10.1
97R. HNO + N = H + N2O		10.7	0.5	3.	***** NOTE A. BASED ON T1 (EST)	9.8	11.9	12.0	12.1

TABLE 3-b (CONTINUED)

RECOMMENDED RATES	REACTION	LOG A	B	C	COMMENTS	TEMP., KELVIN		
						1500	2000	2500
						LOG K		
98F.	$H + N_2O = HO + N_2$	13.9	0.	15.	BASED ON B9C CRIT EVAL 700-2500K	3.0	11.7	12.3
99F.	$H + O + M = HO + M$	15.9	0.	0.	BASED ON S30 LIMITED DATA REF B88 GIVES NO REC	15.9	15.9	15.9
100R.	$HO + O = H + O_2$	13.4	0.	0.	BASED ON B88, W31 NOTE REF B88 REC'S FOR 100F. A = 14.4, R = 0., C = 16.8 CRIT EVAL 300-2000K	13.4	13.4	13.4
101F.	$H + O_2 + M = HO_2 + M$	15.2	0.	1.	BASED ON B88 M = AR	14.5	15.1	15.1
102F.	$HN + HN = H_2 + N_2$				FOUR CENTER PROBABLY SLOW D8 GIVES 14 AT 2000K BAHN CITES 13 FROM REF M8 (ERROR)			
103F.	$HN + HO = H_2 + NO$				FOUR CENTER PROBABLY SLOW			
104F.	$HN + HO = H_2O + N$	11.7	0.5	2.	***** NOTE A. BASED ON T1 (EST)	11.5	13.0	13.1
105R.	$HNO + N = HN + NO$	11.0	0.5	2.	***** NOTE A. BASED ON T1 (EST)	10.8	12.3	12.4
106F.	$HN + NO_2 = HNO + NO$	11.3	0.5	5.	***** NOTE A. BASED ON T1 (EST)	8.9	12.2	12.4
107F.	$HN + N_2O = HNO + N_2$	11.0	0.5	3.	***** NOTE A. BASED ON T1 (EST)	10.1	12.2	12.3

TABLE 3-6 (CONTINUED)

RECOMMENDED RATES			1500-2500K		9/30/73		TEMP., KELVIN		
REACTION	LOG A	B	C	COMMENTS	300	LOG K	1500	2000	2500
108F. $\text{HN} + \text{O} = \text{HO} + \text{N}$	11.8	0.5	8.	SRI ESTIMATE QPR NO. 2, 2/15/73 BASED ON TRANS STATE PARAMETERS $M = 7$, $S = -22$, $CP = -3$	7.2	12.2	12.6		12.8
109F. $\text{HN} + \text{O} + \text{M} = \text{HNO} + \text{M}$	16.0	-0.5	0.	***** NOTE A. BASED ON T1 (EST)	14.8		14.4	14.3	14.3
110R. $\text{HNO} + \text{O} = \text{HN} + \text{O}_2$	11.0	0.5	7.	***** NOTE A. BASED ON T1 (EST)	7.1		11.6	11.9	12.1
111R. $\text{HO}_2 + \text{N} = \text{HN} + \text{O}_2$	11.	0.	0.	***** NOTE C. BASED ON K25 (XPT) LOWER LIMIT	11.0		11.0	11.0	11.0
112R. $\text{HO} + \text{N} + \text{M} = \text{HNO} + \text{M}$	15.0	-0.5	0.	***** NOTE A. BASED ON T1 (EST)	13.8		13.4	13.3	13.3
113F. $\text{HNO} + \text{HO} = \text{H}_2\text{O} + \text{NO}$	14.0 12.	0. 0.	0. 1.	BASED ON H31 SRI ESTIMATE 3/28/73	14.0 11.3		14.0 11.9	14.0 11.9	14.0 11.9
114F. $\text{HNO} + \text{NO} = \text{HO} + \text{N}_2\text{O}$	12.3	0.	26.	BASED ON W23 REEXAMINATION OF EXISTING H2-NO DATA 1000-1300K	-6.6		8.5	9.5	10.0
115F. $\text{HNO} + \text{O} = \text{HO} + \text{NO}$	11.7	0.5	0.	***** NOTE A. BASED ON T1 (EST)	12.9		13.3	13.4	13.4
116R. $\text{H}_2 + \text{O}_2 = \text{HO} + \text{HO}$	12.4	0.	39.	BASED ON R2 1400-2500K REF B88 INDICATES R2 PROBABLY VALID BUT MAKES NO REC	-16.0		6.7	8.1	9.0

TABLE 3-6 (CONTINUED)

RECOMMENDED RATES		1500-2500K		9/30/73		TEMP, KELVIN	
REACTION		LOG A	B	C	COMMENTS	300	1500 2000 2500 LOG K
117F. $\text{HO} + \text{HO} = \text{H}_2\text{O} + \text{O}$		12.8	0.	1.	BASED ON B88 EVALUATION 300-2000K	12.1	12.7 12.7 12.7
118F. $\text{HO} + \text{HO}_2 = \text{H}_2\text{O} + \text{O}_2$		13.	0.	1.	BASED ON L11 H37 INDIC 14 AT 300K B88 SUGGESTS 12.8 AS LOWER LIMIT AT 300K	12.3	12.9 12.9 12.9
119F. $\text{HO} + \text{NO} = \text{HO}_2 + \text{N}$					NO DATA WILL ESTIMATE		
120R. $\text{HO}_2 + \text{NO} = \text{HO} + \text{NO}_2$		12.	0.	3.	SRI ESTIMATE 3/28/73 LOWER THAN J12,N6 WITHIN LIMITS L11	9.8	11.6 11.7 11.7
121R. $\text{HO}_2 + \text{M} = \text{HO} + \text{O} + \text{M}$		15.6	-1.5	64.	SRI ESTIMATE 4/6/73 NO VALID DATA (B98)	-34.7	1.5 3.7 4.9
122R. $\text{HO}_2 + \text{O} = \text{HO} + \text{O}_2$		13.7	0.	1.	BASED ON L11 300-1000K LIMITED INFO	13.0	13.6 13.6 13.6
123F. $\text{H}_2 + \text{NO}_2 = \text{H}_2\text{O} + \text{NO}$					SLOW K=3.5 AT 700K		
124R. $\text{N}_2 + \text{M} = \text{N} + \text{N} + \text{M}$		21.6	-1.6	225.	BASED ON B90 M = N2	-146.3	-16.3 -8.3 -3.5
125F. $\text{N} + \text{NO} = \text{N}_2 + \text{O}$		13.2	0.	0.	BASED ON B90 CRITICAL EVALUATION	13.2	13.2 13.2 13.2
		11.8	0.5	0.	SRI ESTIMATE QPR NO. 2, 2/15/73 BASED ON TRANS STATE PARAMETERS H = -1, S = -22, CP = -3	13.0	13.4 13.5 13.5

TABLE 3-6 (CONTINUED)

RECOMMENDED RATES	REACTION	LOG A	B	C	COMMENTS	300	TEMP, KELVIN		
							1500	2000	2500
							LOG K		
126F.	N + NO + M = N2O + M				STABILIZ NOT LIKELY PROBABLY GOES TO N2 + O S30-NO EVIDENCE				
127F.	N + NO2 = NO + NO	12.6	0.	0.	BASED ON P10 USING B = 0, C = 0 B90 INDICATES P10 UPPER LIMIT PROB 2.5X LOWER	12.6	12.6	12.6	12.6
128F.	N + NO2 = N2 + O + O	12.2	0.	0.	BASED ON P10 USING B = 0, C = 0 UPPER LIMIT	12.2	12.2	12.2	12.2
129F.	N + NO2 = N2 + O2	12.0	0.	0.	BASED ON P10 USING B = 0, C = 0 PROBABLY UPPER LIMIT	12.0	12.0	12.0	12.0
130F.	N + NO2 = N2O + O	12.7	0.	0.	BASED ON P10 USING B = 0, C = 0	12.7	12.7	12.7	12.7
131F.	N + N2O = NO + N2	8.7	0.	10.	***** BASED ON B19 (SEL)	1.4	7.2	7.6	7.8
132R.	NO + M = N + O + M	20.6	-1.5	150.	BASED ON B90 M = AR, N2, O2 CAUTION RECOMMENDED BASED ON M26, M = AR (O) FORMATION MEAS.	-92.4	-6.0	-0.7	2.4
133F.	N + O2 = NO + O	9.8	1.	6.3	BASED ON B90 EVALUATION 300-3000K SRI ESTIMATE QPR NO. 2, 2/15/73 BASED ON TRANS STATE PARAMETERS H = 7, S = -22, CP = -3	-93.7	-7.5	-2.1	1.2
		11.8	0.5	8.		7.7	12.1	12.4	12.6
						7.2	12.2	12.6	12.8

TABLE 3-6 (CONTINUED)

RECOMMENDED RATES	REACTION	LOG A	B	C	COMMENTS	300	TEMP., KELVIN		
							1500	2000	2500
							LOG K		
134F.	NO + NO = N2 + O2				SPIN FORBIDDEN PROBABLY SLOW OLD DATA DID NOT MEASURE THIS RX ACTUALLY MEAS 135F				
135R.	N2O + O = NO + NO	14.0	0.	28.	BASED ON B90 EVAL 1200-2000K SAME RATE AS 141R	-6.4	9.9	10.9	11.6
136F.	NO + NO2 = N2O + O2				NO TRANSITION STATE NO EXPTL EVIDENCE BASED ON B19 (EST)	-31.7	3.3	5.4	6.8
137F.	NO + N2O = NO2 + N2	12.0	0.	60.	BASED ON K30 USING A = 12.3 NO RECENT DATA	-16.8	6.5	7.9	8.8
138R.	NO2 + M = NO + O + M	12.3	0.	40.					
139R.	NO2 + M = NO + O + M	16.0	0.	65.	BASED ON B90, T4 M = AR, O2 1400-2400K	-31.4	6.5	8.9	10.3
140R.	NO2 + O = NO + O2	13.	0.	1.	BASED ON B53 CRIT EVAL 300-600K NO HI T DATA	12.3	12.9	12.9	12.9
141R.	N2O + M = N2 + O + M	14.	0.	50.	APPROXIMATE COVERS LIMITED DATA IN 1500-2500K RANGE	-22.4	6.7	8.5	9.6
142R.	N2O + O = N2 + O2	14.	0.	28.	BASED ON B90 REC 1200-2000K SAME RATE AS 135R	-6.4	9.9	10.9	11.6
143R.	O2 + M = O + O + M	18.4	-1.	118.7	BASED ON J4, M = AR	-70.6	-2.1	2.1	4.6
		19.4	-1.	118.7	BASED ON J4, M = O2 CRITICAL EVALUATION WIDE TEMP RANGE 1000-8000K FOR O2 300-15000K FOR AR	-69.6	-1.1	3.1	5.6

In the screening studies, reactions could be eliminated for one of three reasons:

1. The reaction itself is too slow to play a major role for any species.
2. The reaction is part of a loop which merely returns its starting material.
3. A species involved in the reaction is of no importance in either combustion or pollutant formation.

These practical considerations must be handled with some caution since reaction elimination based on species could vary with the goals of the screening procedure. For example, calculations oriented primarily toward heat release and combustion efficiency could easily ignore NO forming reactions since these reactions play a very small role in that respect. At peak NO formation rate, the NO forming reactions are involved in only about 0.01% of the O atom appearance or disappearance reactions. Since NO is of prime interest in these calculations, such reactions must be carefully retained. On the other hand, since soot is not likely to form in methane/air combustion unless substantial concentrations of hydrocarbons remain at the end of the combustion zone, reactions precursor to soot formation can probably be ignored with a fair degree of safety as long as calculations are restricted to the region of 80%-120% stoichiometric air at atmospheric pressure.

While progress toward the definition of a "minimum reaction set" is an ultimate goal it is more important initially to appreciate the chemistry of the coupled reactions. With 322 possible unimolecular and bimolecular reactions which can be written for the 25 species in the kinetics survey, it is entirely possible that some reaction beyond those 142 reactions for which rate information was reported in the literature might be of importance. While many of the reactions not reported in the literature are not elementary reactions an evaluation of the potential importance of each of the remaining reactions will be undertaken as a step towards the complete evaluation of the combustion/pollutant formation mechanism for the 25 species considered.

3.4 Results of Theoretical Calculations for Methane/Air

Screening calculations have been performed, using the interim (September 1973) recommended rates for the kinetics survey, to gain insight into the major reaction paths and major reactions in the coupled combustion/pollutant formation for methane/air. The interim rates have since been superseded by the recommended rates given in Reference 3-1 but the results obtained from these calculations are instructive for the overall features uncovered. However, the reader should be aware that the quantitative details would be different if the revised rates were used and that the reaction set used for these calculations was not complete. Therefore potentially important paths for NO_x formation have been omitted from these calculations.

Most of the calculations were accomplished under isothermal conditions at the adiabatic flame temperature as discussed earlier. These isothermal calculations result in temperatures and reaction rates in the early combustion zone which are higher than those observed experimentally. Therefore, the calculations indicate a hydrocarbon burnout rate which is more rapid than for the case of an adiabatic flame. However, the essential features of the combustion are preserved as indicated by comparison with calculations of adiabatic ignition from room temperature. The concentrations calculated for the intermediates remain basically the same. The concentration levels are sufficiently close for screening purposes although the overshoots tend to reach higher concentrations (but for shorter times) in the isothermal case.

Concentrations of selected species as a function of time for plug flow reaction at stoichiometries of 80%, 100% and 120% stoichiometric air are given in Tables 3-7, 3-8 and 3-9 respectively. It should be emphasized that these are only preliminary calculations based on the limited number of reactions reported in the literature. Such calculations are highly informative but must be followed by more complete calculations for further elucidation. The reaction times selected for these tables are illustrative of some of the zone divisions to be discussed in Section 3.5. At this point a discussion of the species concentrations themselves will be presented.

3.4.1 80% Stoichiometric Air

In Table 3-7 for 80% stoichiometric air, the first column of concentrations indicates the initial conditions corresponding to zero time. After 35 μsec (assuming no ignition delay) the methane is essentially gone. The CO has built up to essentially its maximum concentration and some of the CO has already reacted to form CO_2 . Before CO reaches its peak, substantial concentrations of hydrocarbon intermediates as well as CHO and CH_2O are observed but these have dropped off by the time CO has peaked. Concentrations of the radical intermediates H, HO, and O reach their peaks at about the same time as CO, with H being 1.2 mole %, HO being 1.1% and O being 0.4%. Molecular hydrogen has also reached a high level (2.3%) although water is much higher at 18.0%. NO has not yet formed to a substantial extent, being on the order of 0.2 ppm but its rate of formation,

as indicated in Table 3-7, is quite high. Two species (N and NO₂) present in very low concentrations have quite different orders of importance. Atomic nitrogen plays a major role in NO formation* through $N + O_2$ and $N + OH$ and it is formed almost exclusively by the reaction $N_2 + O \rightarrow NO + N$. Thus N concentration is essentially determined by the O concentration. On the other hand, NO₂ never builds up to any substantial extent in the combustion zone and, almost as quickly as it is formed, it returns to NO.

After 600 μ sec CO and CO₂ have almost reached their ultimate concentrations. Species H, HO and O, while having decreased in concentration, are still substantially above their equilibrium values. The concentrations of H₂ and H₂O have essentially leveled off while NO is still increasing but at a much slower rate.

After 4.6 msec, species concentrations remain fairly constant, and although O and N atom concentrations are still somewhat above equilibrium, they are not high enough to cause substantial incremental NO formation.

3.4.2 100% Stoichiometric Air

Table 3-8 summarizes the kinetics calculations for 100% stoichiometric air. After 12 μ sec (no ignition delay) methane has disappeared and CO has reached its peak. Some of the CO has already reacted to CO₂. Concentration of H₂ has reached 2% and H₂O has reached 13.6%. Atomic nitrogen is over 0.1 ppm, a high mole fraction for this intermediate, while NO has just started to form, being slightly in excess of 1 ppm. Molecular oxygen has dropped from its initial concentration of 19% to about 4% on its way to 0.5%. The rate of NO formation, at this point, is extremely high (320,000 ppm/sec) but is dropping off quite rapidly as the concentration of oxygen atom decreases. By the time 200 μ sec have elapsed the rate of NO formation has dropped to 90,000 ppm/sec and about 50 ppm of NO has formed.

After 10 msec, CO and CO₂ concentrations have leveled off at about 1% and 8% respectively. The concentrations of radical intermediates have dropped off to within 150% to 200% of their equilibrated values and the NO formation rate has dropped off to 7,000 ppm/sec. The calculated concentration of 200 ppm represents an average formation rate of 20,000 ppm/sec, compared to an average formation rate of 150,000 ppm/sec up to 0.3 msec, and an average formation rate of 5,500 ppm/sec up to 100 msec. At the 100 msec point the instantaneous formation rate has dropped to less than 4,000 ppm/sec. The rapid initial formation of NO, even though probably overpredicted because of the high initial temperature, bears many resemblances to what might be called "prompt NO" (3-2).

* It should be noted that recommended rates were not available at the time of these calculations for additional reactions, which are potentially important for NO formation. Therefore, the inferences made here should be regarded as preliminary and subject to further refinement.

(3-2) Fenimore, C. P., 13th Symposium (International) on Combustion, p. 373, The Combustion Institute, 1971.

TABLE 3-7

KINETIC CALCULATIONS FOR PLUG FLOW CH_4 /AIR COMBUSTION AT 80% STOICH AIR

$T = 2097^\circ\text{K}$

Species	Branching Zone		Relaxation Zone		Post-Flame Zone
	$t = 0$	35 μ sec	600 μ sec	4.6 msec	10 msec
CH_4	11.6%	14 ppm	--	--	--
CO	--	9.4%	5.4%	5.3%	5.3%
CO_2	--	1.3%	5.7%	5.8%	5.8%
H	--	1.2%	0.4%	0.07%	0.06%
HO	--	1.1%	0.2%	0.05%	0.04%
H_2	--	2.3%	3.5%	3.5%	3.5%
H_2O	--	18.0%	18.3%	18.6%	18.6%
N	--	2.7×10^{-2} ppm	1.0×10^{-2} ppm	1.6×10^{-3} ppm	1.2×10^{-3} ppm
NO	--	0.2 ppm	4.8 ppm	5.7 ppm	5.9 ppm
NO_2	--	10^{-4} ppm	10^{-3} ppm	10^{-4} ppm	5×10^{-5} ppm
O	--	0.4%	0.02%	0.0007%	0.0004%
O_2	18.6%	1.4%	0.04%	0.002%	0.001%
$\frac{d(\text{NO})}{dt}$	--	32,000 ppm/sec	1,600 ppm/sec	59 ppm/sec	36 ppm/sec

Note: See Section 3-5 for discussion of "zones".

TABLE 3-8

KINETIC CALCULATIONS FOR PLUG FLOW CH₄/AIR COMBUSTION AT 100% STOICH AIR

T = 2222°K

Species	Branching Zone		Relaxation Zone		Post-Flame Zone
	t = 0	12 μ sec	300 μ sec	10 msec	100 msec
CH ₄	9.5%	5×10^{-2} ppm	--	--	--
CO	--	7.7%	3.1%	1.0%	0.8%
CO ₂	--	1.1%	6.1%	8.4%	8.6%
H	--	2.0%	0.7%	0.06%	0.04%
HO	--	2.0%	1.1%	0.4%	0.3%
H ₂	--	2.0%	1.4%	0.4%	0.3%
H ₂ O	--	13.6%	16.1%	18.2%	18.4%
N	--	0.11 ppm	0.06 ppm	0.02 ppm	0.01 ppm
NO	--	1.4 ppm	49 ppm	200 ppm	550 ppm
NO ₂	--	0.0004 ppm	0.02 ppm	0.04 ppm	0.09 ppm
O	--	1.4%	0.4%	0.03%	0.02%
O ₂	19.0%	4.1%	1.9%	0.6%	0.5%
$\frac{d(NO)}{dt}$	--	320,000 ppm/sec	90,000 ppm/sec	7,000 ppm/sec	3,700 ppm/sec

Note: See Section 3.5 for discussion of "zones".

TABLE 3-9

KINETIC CALCULATIONS FOR PLUG FLOW CH_4 /AIR COMBUSTION AT 120% STOICH AIR

$T = 2044^\circ\text{K}$

Species	Branching Zone		Relaxation Zone		Post-Flame Zone
	$t = 0$	12 μ sec	900 μ sec	40 msec	500 msec
CH_4	8.0%	8 ppm	--	--	--
CO	--	6.7%	0.9%	0.09%	0.08%
CO_2	--	0.8%	7.1%	7.9%	7.9%
H	--	1.6%	0.2%	0.004%	0.004%
HO	--	1.6%	0.7%	0.2%	0.2%
H_2	--	1.3%	0.4%	0.04%	0.04%
H_2O	--	12.2%	15.1%	15.9%	15.9%
H	--	0.02 ppm	0.008 ppm	0.0009 ppm	0.0009
NO	--	0.3 ppm	22 ppm	86 ppm	483 ppm
NO_2	--	--	--	--	--
O	--	1.5%	0.2%	0.02%	0.02%
O_2	19.3%	6.3%	3.6%	3.2%	3.2%
$\frac{d(\text{NO})}{dt}$	--	85,000 ppm/sec	12,000 ppm/sec	1,000 ppm/sec	900 ppm/sec

Note: See Section 3.5 for discussion of "zones".

3.4.3 120% Stoichiometric Air

At 120% stoichiometric air (Table 3-9) the basic features of the concentration profiles are the same as with lower air supply, except that the N atom concentrations are lower and NO is produced more slowly. At the 12 μ sec point it can be seen that the concentrations of H, HO, and O are almost the same as in the 100% stoichiometric air case, yet the N atom concentration is lower by a factor of 5. As will be discussed later, N atoms are produced primarily by the reaction $N_2 + O \rightarrow NO + N$ which has a 75 kcal activation energy and, therefore, proceeds more slowly at 2044°K than it does at 2222°K. By the same token, NO is produced more slowly, and again its concentration is lower by a factor of 4 to 5 throughout. If the temperature were increased to 2222°K, one might expect more rapid NO formation at 120% stoichiometric air than at 100% stoichiometric air. Indeed, this is observed experimentally (see Section 3.5).

3.5 Discussion

Theoretical calculations based on the recommended rates from the kinetics survey of methane combustion indicate that, at all mixture ratios studied, the combustion process under plug flow conditions can be divided into three zones. For identification and convenience, these zones will be called the branching zone, the relaxation zone and the post-flame zone. The basic characteristics of each zone are as follows: (it should be noted that the reaction times, provided for reference would vary with the temperature profile. The features discussed are valid for the general combustion case.)

(1) The Branching Zone (10-100 μ sec duration following ignition delay, if any):

- is the zone in which the hydrocarbon is consumed.
- the hydrocarbon goes primarily to CO and H₂O although some CO₂ and H₂ are formed in this zone.
- the most important feature of this zone is that the radical intermediates such as O, H, HO, etc., build up to extremely high concentrations and N atoms are substantially in excess of equilibrium although at low absolute concentrations.
- the individual intermediates do not appear to reach maximum concentrations at precisely the same time, but the point at which methane concentration has reached a low level (on the order of 1 ppm) coincides roughly with the peak concentrations of the intermediates.
- because of the short times involved, the NO concentration at the end of the branching zone is quite low (on the order of 1 ppm) but the rate of NO formation is at its peak because of the high concentrations of the intermediates.
- while very little NO is produced in this zone, it is the high concentrations of intermediates which set the stage for rapid NO formation and, therefore, the kinetic details of this zone are extremely important.

(2) The Relaxation Zone (5-50 msec duration):

- is the zone in which the concentrations of intermediates approach their ultimate values at the specified temperature.
- the end of this zone is more difficult to define because the approach to equilibrium is asymptotic. However, the precise definition is not critical since it is an arbitrary separation to distinguish this zone from the post-flame zone in which intermediates have essentially reached equilibrium. One possible definition of the end of the zone is the point at which intermediate concentrations (O, OH, H, N) have reached, e.g., 200% (or 150% or 110%) of their equilibrium values. Another definition might involve the rate of change of concentration of these intermediates.
- in this zone, the rapid formation of NO takes place. However, the stage has already been set by the high concentrations of intermediates produced in the branching zone.
- the primary NO forming reactions in this zone, using the preliminary rate survey, appear to be $N_2 + O$, $N + O_2$ and $N + HO$. However, the concentrations of these species are not yet equilibrated in this zone. Thus, the rate of formation of NO can be substantially higher than that predicted by classical Zeldovich kinetics.
- even without "prompt NO" reactions, which may involve nitrogeneous species other than atomic and molecular nitrogen, the high concentrations of intermediates do result in very rapid or "prompt" NO formation.
- it is still worth searching for "prompt NO" reactions. The master set of 322 reactions includes several reactions for which rate data are currently unavailable. An evaluation of the potential importance of each of the 322 reactions would provide a starting point for a further screening effort. With reasonable estimates for the resulting set, the screening framework would provide a basis for the evaluation of reactions of importance.
- the formation of N atoms in these calculation is found to result almost exclusively from the reaction $N_2 + O = NO + N$. The destruction of N atoms is primarily through NO forming reactions $N + O_2 = NO + O$ and $N + HO = NO + H$. Other N-forming reactions should be sought in the extension of this kinetics survey.
- the formation of O atoms is found to result almost exclusively from the reaction $H + O_2 = HO + O$.

- the formation of H atoms is found to result, in good part, from the reaction $\text{CO} + \text{HO} = \text{CO}_2 + \text{H}$. The destruction of H atoms occurs, in good part, through the reaction $\text{H} + \text{O}_2 = \text{HO} + \text{O}$.
- HO is formed in the $\text{H} + \text{O}_2$ reaction and destroyed in $\text{CO} + \text{HO}$ (although not exclusively).
- to summarize the nature of the rapid NO formation observed in kinetic calculations using the preliminary rate survey:
 - + the NO formed depends primarily on the concentrations of N and O atoms.
 - + N atom formation depends on the O atom concentration through $\text{N}_2 + \text{O} = \text{NO} + \text{N}$. N atom destruction depends on $\text{HO} + \text{N} = \text{NO} + \text{H}$ and $\text{N} + \text{O}_2 = \text{NO} + \text{O}$.
 - + O atom formation depends on the H atom concentration through $\text{H} + \text{O}_2 = \text{HO} + \text{O}$. O atom destruction is primarily through reaction with CHO at the branching/equilibration interface and through reaction with H_2O at the equilibration/post flame interface.
 - + the H atom formation depends on the CO and HO concentrations through $\text{CO} + \text{HO} = \text{CO}_2 + \text{H}$. Destruction of H atoms occurs through recombination with HO and CHO and by the $\text{H} + \text{O}_2$ reaction.
 - + the initial concentrations of CO, HO, H and O in the equilibration zone are determined by reactions occurring in the branching zone.

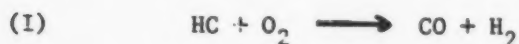
(3) The Post-Flame Zone (50 μsec and beyond):

- the concentrations of intermediates are either equilibrated, or nearly so, and the modified Zeldovich treatment (including steady state assumptions) is a good approximation of the behavior in this zone.

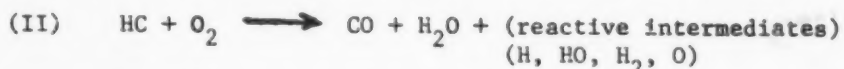
The above observations lead one back to questions about a quasi-global approach in which the hydrocarbon can partially oxidize in one step and the intermediates can burn out in a detailed manner. The behavior of the hydrocarbon in the branching zone, at first glance, appears to be quasi-global in nature. Hydrocarbon reacts very rapidly to produce CO and H_2O before a substantial concentration of NO is produced. However, in addition to CO and H_2O , the hydrocarbon disappearance results in the appearance of high concentrations of other reactive intermediates.

In the Fourteenth Symposium (International) on Combustion, a paper by Engleman *et al.* (3-3) demonstrated that while CO and H_2 combustion in a jet-stirred combustor could be modeled by detailed kinetics, a quasi-global model for propane was not adequate to predict NO formation. The global hydrocarbon step in that mechanism was

3-3 V. S. Engleman, W. Bartok, J. P. Longwell, and R. B. Edelman, Fourteenth Symposium (International) on Combustion, p. 755, The Combustion Institute (1973).



The CO and H₂ were then allowed to complete combustion by a detailed mechanism. It appears from detailed modeling that the global hydrocarbon step is actually



In global step I an approximation to the true picture is made by assuming all the hydrogen in the hydrocarbon goes through H₂, a species which can participate actively in branching reactions.

Thus, the quasi-global mechanism for hydrocarbon combustion achieves an approximation of the overshoot of equilibrium by making the assumption that the hydrocarbon is converted in one step to CO and H₂ (see Appendix C). The H₂ then participates in branching reactions which produce high concentrations of intermediates similar to those found in detailed calculations. However, detailed calculations indicate that the actual mechanism produces high concentrations of active intermediates while the hydrocarbon is converted to CO and H₂O (see Tables 3-7, 3-8, and 3-9 for species concentrations at the end of the branching zone). These calculations indicate that the quasi-global mechanism does not adequately predict the overshoot.

3.6 Reactions of Importance at the Interface Between the Branching Zone and the Relaxation Zone

The interface between the branching zone and the relaxation zone is an extremely important region from the standpoint of rapid formation of NO in the flame zone. This interface has been defined in a previous section as the location where certain combustion intermediates have reached their peak concentrations. Reactions of importance for formation and destruction of these intermediates and for NO will be discussed in this section. It should be reiterated here (and will be discussed further in the next section) that the events which occur within the branching zone are very important for the establishment of the high concentrations of intermediates. The screening that has been done thus far has been more concerned with determining controlling reactions and less concerned with the absolute magnitude of rate constants or the concentrations predicted by the calculations. However, the balance among the reactants, intermediates, products has been of major concern, since the relative concentrations help determine the magnitude and direction of the individual reactions

At the end of the branching zone, NO is just barely starting to form in ppm level concentrations. At this point the concentrations of intermediates are high and the rate of NO formation is at its peak. It is instructive to consider some of the important reactions at this point. It should be emphasized that while the comments in this section are based on detailed calculation using a large number of reactions, not all possible reactions have been included because rate information was unavailable in

some cases. The inclusion of "prompt NO" reactions in these calculations could result in changes in the NO mechanism under specific conditions.* Most of the observations discussed below, however, are expected to be valid.

At the point where carbon monoxide starts to be destroyed more rapidly than it is being produced, the primary destruction reaction is



which accounts for 70-80% of its destruction. This reaction also produces most of the H at this point although within the branching zone most of the H comes from hydrocarbon fragments.

The H atoms, at this point, are being destroyed by the reaction



which accounts for 40-50% of its destruction and also produces essentially all of the O atoms. H is also being destroyed (25-30%) by



and (10-15%) by



The O atoms, as indicated above are formed entirely** by



at the interface, and are destroyed (45-50%) by



and (25-35%) by***



* "Prompt NO" reactions, in this context, are those involving hydrocarbon fragments which result in production of N atoms; e.g. $\text{CH} + \text{N}_2 \rightarrow \text{N}$.

** In the branching zone itself, some O atoms are formed by $\text{HO} + \text{HO} \rightarrow \text{H}_2\text{O} + \text{O}$.

*** In part of the branching zone this reaction is a producer of oxygen atoms.

Based on calculations which do not consider the role of hydrocarbon fragments in the production of N atoms, the following observations are noted. While O atoms are extremely important for the production of NO, the NO reactions are relatively unimportant in determining O atom concentrations. NO reactions account for less than 1% of the total O atom production and destruction. The main NO-producing reaction at the interface is



which produces about half of the NO and essentially all of the N atoms. The reaction



produces 25-30% of the NO and the reaction



produces about 20% of the NO at the interface. It will be noted that all of the NO reactions also involve N atoms. In fact the N atoms are produced and destroyed by these reactions almost exclusively. More than 99% of the N atoms are produced by



while about 60% of the N is destroyed by



and 40% is destroyed by



Using only the reactions for which rate data are available, at one point within the branching zone as much as 25% of N atoms are destroyed by reactions with hydrocarbon fragments to produce CHN and CN. These species do not react directly to produce NO, but produce either N atoms or N₂ molecules through subsequent reactions. However, the main N atom reactions for production and destruction in these calculations were those involving NO.

3.7 Comparison of Theoretical Calculations with Experimental Results

The comparisons between theoretical calculations discussed in Section 3.4 and the experimental results discussed in Section 3 are encouraging. As expected, because of the artificial constraints placed on the temperature in the theoretical calculations, the NO levels for the plug-flow simulation of the flat flame are somewhat overpredicted. However, at this point it is not certain whether the overpredictions are more a result of the high temperatures early in the calculations or because the rate constants used for NO formation reactions may be too high. The latter interpretation is favored by the fact that the theoretical overprediction continues to be observed in the post-flame zone. The temperature profile used for reaction screening may have a less dramatic effect than initially expected because the major portion of the reactions involving heat release are completed before substantial NO has formed.

The theoretical-experimental comparisons under stoichiometric or excess air conditions are the closest. Under fuel rich conditions, NO concentrations are underpredicted. These underpredictions could be caused by the lack of reactions between hydrocarbon fragments and molecular nitrogen, or the high rate of disappearance of active oxygen-containing intermediates. The high rate of disappearance of both hydrocarbon species and oxygen-containing intermediates would be caused by the use of isothermal conditions in the combustion zone where experimentally the temperature is increasing from room temperature to flame temperature.

Under stoichiometric air conditions, plug flow calculations overpredict experimentally measured concentrations of NO in the post-flame zone by about a factor of two. Theoretical calculations indicate 700 ppm at 150 msec while only 350 ppm are measured; 1200 ppm are calculated at 300 msec while 600 ppm are measured. In the post-flame zone the rate of NO formation between 200 and 500 msec is measured to be 1500 ppm/sec while the calculated rate is about 3000 ppm/sec. The comparison between theory and experiment, on a preliminary basis, indicate that a reduction of the NO formation rate constants by a factor of two could bring theory in line with experiment. However, additional theoretical analysis is required before such reductions may be considered permissible.

A similar picture is obtained at 120 percent stoichiometric air. Experimental measurements at 40 msec indicate concentrations in the 40-50 ppm range while calculations indicate about 90 ppm. Measurements indicate concentrations of about 170 ppm at 500 msec while calculations indicate about 480 ppm. The rate of NO formation is measured to be about 400 ppm/sec between 300 and 500 msec while calculations indicate about 900 ppm/sec.

Under fuel rich conditions experimental measurements indicate a very rapid formation of NO in the flame zone and essentially a zero net formation rate thereafter. Calculations indicate a similar behavior, with essentially all the NO formed in the relaxation zone, and little or none in the branching or post-flame zones. However, the levels of NO formed experimentally are much higher than those calculated in the screening

studies. This is likely to be caused, in part, by the overly rapid calculated depletion of methane and oxygen in the branching zone because of the high temperature assumed. However, another possible explanation is because of the lack of reactions involving hydrocarbons in NO formation in these calculations. This possibility will be pursued further in Phase II of this study. Measured NO formation in the flame zone is on the order of 60 ppm, while the calculated value is on the order of 6 ppm.

4. CONCLUSIONS

1. The survey of 142 reactions appearing in the literature for 25 species in the CH_4/air system resulted in recommended rates for 127 reactions to be used for reaction screening. Since 322 reactions could be postulated for these 25 species, additional attention is needed to determine if any of these additional reactions could be important.
2. Reaction screening using only these 127 reactions or smaller subsets indicates that between 80% and 120% stoichiometric air for methane combustion:
 - NO formation rate is controlled primarily by oxygen atom concentration.
 - Oxygen atom concentrations are substantially above equilibrium in the branching zone before significant NO has formed.
 - Oxygen atom concentrations have peaked before significant NO has formed.
 - Oxygen atom concentration controls formation of N atoms which participate in NO reactions. N atom destruction results in NO formation by $\text{N} + \text{OH}$ and $\text{N} + \text{O}_2$.
 - While reaction screening for the 127 reaction set has not uncovered reactions other than $\text{N}_2 + \text{O}$ which might produce N atoms in the branching zone, it is still worth pursuing the search for other N-forming reactions that might occur in the branching zone. Such reactions might produce more substantial overshoots of N atom concentrations which could provide more rapid NO formation early in the flame zone.
3. Reaction screening from the 127 reaction set has resulted in narrowing down the number of reactions that need be considered for NO formation under the conditions studied. Caution must be exercised not to extrapolate these conclusions outside the range studied without rechecking the calculations under the new conditions. Further screening will be required when other reactions from the 322 reaction set (25 species) are tested for importance.
4. As additional reactions are studied or estimated the minimum set of reactions may change:
 - The new reaction may be added to the set by itself if it provides a new path between two important intermediates (can affect any zone).
 - The new reaction may result in the rapid destruction of an intermediate as it is formed, preventing overshoot from occurring. In that case the minimum set would be reduced by eliminating reactions of that intermediate (branching zone).
 - The new reaction may result in rapid production of an intermediate in the branching zone and corresponding overshoot in its concentration. Thus, a new intermediate may play a role in NO formation - possibly HN, CHN or CN (branching zone).

5. Premixed flat and focused flames as well as laminar and turbulent diffusion flames have been studied in the multiburner under both cold-and hot-wall conditons:
 - The burners appeared to behave as idealized examples of the types they represented. Concentrations and temperature profiles have been measured in these flames.
 - Under certain conditions the curvature in NO formation (non-linear extrapolation back to the origin) could be measured.
6. Comparisons of isothermal plug-flow calculations at the adiabatic flame temperature with experimental data indicate:
 - NO formation is overpredicted by a factor of two in both the flame zone and post-flame zone for fuel-lean combustion and in the post-flame zone for stoichiometric air conditions. NO formation is underpredicted for fuel rich combustion by an order of magnitude.
 - + Overprediction in the post flame zone under fuel lean conditions, where intermediates other than NO have reached essentially equilibrium concentrations, indicate that the controlling NO formation rate, $N_2 + O = NO + N$, should be reduced by a factor of two. (This reaction has a high activation energy and therefore temperature uncertainty must be taken into account.)
 - + The possible interaction between hydrocarbon species and nitrogenous species should be investigated to determine their possible role under fuel-rich conditions.
 - Extremely high concentration gradients are predicted by the plug flow calculations which do not include diffusion effects. In a real system, such concentration gradients would be smoothed somewhat by diffusion.
 - For the purpose of the present study that concerns itself with the chemistry of combustion and pollutant formation reactions, it would be desirable to eliminate diffusion effects from the experimental system. To achieve that goal, the development of an adiabatic stirred combustor is indicated. Development of this combustor type which incorporates the principles of mixing in the jet-stirred combustor and adiabatic operation in the multiburner will be discussed in the report on Phase II of this contract study.

APPENDIX A

MASTER LIST OF REACTIONS FOR 25 ALLOWED SPECIES

A	1.	CH	+ CHN	= CH2	+ CN		X	1	
A	2.	CH	+ CHO	= CH2	+ CO		X	2	
A	3.	CH	+ CH2O	= CHO	+ CH2		X	3	
A	.	CH	+ CH2O	= CH3	+ CO	H-O EXCHANGE	X	4	
A	4.	CH	+ CH3	= CH2	+ CH2		X	5	
A	.	CH	+ CH3O	= CHO	+ CH3	O TRANSFER	X	6	
A	.	CH	+ CH3O	= CH2	+ CH2O	H TRANSFER	X	7	
A	.	CH	+ CH3O	= CH4	+ CO	H-O EXCHANGE	X	8	
A	5.	CH	+ CH4	= CH2	+ CH3		X	9	
A	6.	CH	+ CO2	= CHO	+ CO		X	10	
A	8.	CH	+ H	+ M	= CH2	+ M	X	11	
A	.	CH	+ HN	= CHN	+ H	N TRANSFER	X	12	
A	9.	CH	+ HN	= CH2	+ N		X	13	
A	10.	CH	+ HN	= CN	+ H2		X	14	
A	.	CH	+ HNO	= CHN	+ HO	N TRANSFER	X	15	
A	.	CH	+ HNO	= CHO	+ HN	O TRANSFER	X	16	
A	11.	CH	+ HNO	= CH2	+ NO		X	17	
A	.	CH	+ HNO	= CH2O	+ N	(HO) TRANSFER	X	18	
A	.	CH	+ HNO	= CN	+ H2O	H-N EXCHANGE	X	19	
A	12.	CH	+ HO	= CHO	+ H		X	20	
A	13.	CH	+ HO	= CH2	+ O		X	21	
A	.	CH	+ HO	+ M	= CH2O	+ M	(HO) ADDITION	X	22
A	14.	CH	+ HO	= CO	+ H2		X	23	
A	15.	CH	+ HO2	= CHO	+ HO		X	24	
A	16.	CH	+ HO2	= CH2	+ O2		X	25	
A	.	CH	+ HO2	= CH2O	+ O	(HO) TRANSFER	X	26	
A	.	CH	+ HO2	= CO	+ H2O	H-O EXCHANGE	X	27	
A	.	CH	+ HO2	= CO2	+ H2	C-H EXCHANGE	X	28	
A	17.	CH	+ H2	= CH2	+ H		X	29	
A	.	CH	+ H2	+ M	= CH3	+ M	(H2) ADDITION	X	30
A	.	CH	+ H2O	= CHO	+ H2	O TRANSFER	X	31	
A	18.	CH	+ H2O	= CH2	+ HO		X	32	
A	.	CH	+ H2O	= CH2O	+ H	(HO) TRANSFER	X	33	
A	.	CH	+ H2O	= CH3	+ O	(H2) TRANSFER	X	34	
A	.	CH	+ H2O	+ M	= CH3O	+ M	(H2O) ADDITION	X	35
A	.	CH	+ N	+ M	= CHN	+ M	N ADDITION	X	36
A	19.	CH	+ N	= CN	+ H		X	37	
A	.	CH	+ NO	= CHN	+ O	N TRANSFER	X	38	
A	20.	CH	+ NO	= CHO	+ N		X	39	
A	.	CH	+ NO	= CN	+ HO	H-N EXCHANGE	X	40	
A	.	CH	+ NO	= CO	+ HN	H-O EXCHANGE	X	41	
A	.	CH	+ NO2	= CHN	+ O2	N TRANSFER	X	42	
A	.	CH	+ NO2	= CHO	+ NO	O TRANSFER	X	43	
A	.	CH	+ NO2	= CN	+ HO2	H-N EXCHANGE	X	44	
A	.	CH	+ NO2	= CO	+ HNO	H-O EXCHANGE	X	45	
A	.	CH	+ NO2	= CO2	+ HN	C-N EXCHANGE	X	46	
A	21.	CH	+ N2	= CHN	+ N		X	47	
A	.	CH	+ N2	= CN	+ HN	H-N EXCHANGE	X	48	
A	.	CH	+ N2O	= CHN	+ NO	N TRANSFER	X	49	
A	.	CH	+ N2O	= CHO	+ N2	O TRANSFER	X	50	
A	.	CH	+ N2O	= CN	+ HNO	H-N EXCHANGE	X	51	
A	23.	CH	+ O	+ M	= CHO	+ M	X	52	
A	22.	CH	+ O	= CO	+ H		X	53	

MASTER LIST OF REACTIONS FOR 25 ALLOWED SPECIES

A 24.	CH	+ O2	= CH0	+ O		X 54
A 25.	CH	+ O2	= CO	+ HO		X 55
A	CH	+ O2	= CO2	+ H	C TRANSFER	X 56
A 26.	CHN	+ M	= CN	+ H	+ M	X 57
A 27.	CHN	+ CHO	= CH2O	+ CN		X 58
A 28.	CHN	+ CH2	= CH3	+ CN		X 59
A	CHN	+ CH2O	= CH3O	+ CN	H TRANSFER	X 60
A 29.	CHN	+ CH3	= CH4	+ CN		X 61
A 30.	CHN	+ CO	= CH0	+ CN		X 62
A	CHN	+ H	= CH2	+ N	H-N EXCHANGE	X 63
A 31.	CHN	+ H	= CN	+ H2		X 64
A	CHN	+ HN	= CH2	+ H2	H-N EXCHANGE	X 65
A	CHN	+ HNO	= CH2	+ N2O	H-N EXCHANGE	X 66
A	CHN	+ HNO	= CH2O	+ N2	N-(HO) EXCHANGE	X 67
A	CHN	+ HO	= CH0	+ HN	N-O EXCHANGE	X 68
A	CHN	+ HO	= CH2	+ NO	H-N EXCHANGE	X 69
A	CHN	+ HO	= CH2O	+ N	N-(HO) EXCHANGE	X 70
A 32.	CHN	+ HO	= CN	+ H2O		X 71
A	CHN	+ HO2	= CH0	+ HNO	N-O EXCHANGE	X 72
A	CHN	+ HO2	= CH2	+ NO2	H-N EXCHANGE	X 73
A	CHN	+ HO2	= CH2O	+ NO	N-(HO) EXCHANGE	X 74
A	CHN	+ H2	= CH2	+ HN	H-N EXCHANGE	X 75
A	CHN	+ H2	= CH3	+ N	N-(H2) EXCHANGE	X 76
A	CHN	+ H2O	= CH2	+ HNO	H-N EXCHANGE	X 77
A	CHN	+ H2O	= CH2O	+ HN	N-(HO) EXCHANGE	X 78
A	CHN	+ H2O	= CH3	+ NO	N-(H2) EXCHANGE	X 79
A	CHN	+ H2O	= CH3O	+ N	CH TRANSFER	X 80
A 33.	CHN	+ N	= CN	+ HN		X 81
A	CHN	+ NO	= CH0	+ N2	N-O EXCHANGE	X 82
A 34.	CHN	+ NO	= CN	+ HNO		X 83
A	CHN	+ NO2	= CH0	+ N2O	N-O EXCHANGE	X 84
A	CHN	+ O	= CH0	+ N	N-O EXCHANGE	X 85
A 35.	CHN	+ O	= CN	+ HO		X 86
A	CHN	+ O	= CO	+ HN	O-(HN) EXCHANGE	X 87
A	CHN	+ O2	= CH0	+ NO	N-O EXCHANGE	X 88
A	CHN	+ O2	= CN	+ HO2	H TRANSFER	X 89
A	CHN	+ O2	= CO	+ HNO	O-(HN) EXCHANGE	X 90
A	CHN	+ O2	= CO2	+ HN	C TRANSFER	X 91
A 36.	CHO	+ M	= CO	+ H	+ M	X 92
A	CHO	+ CHO	= CH2	+ CO2	H-O EXCHANGE	X 93
A 37.	CHO	+ CHO	= CH2O	+ CO		X 94
A 38.	CHO	+ CH2	= CH3	+ CO		X 95
A	CHO	+ CH2O	= CH3	+ CO2	H-O EXCHANGE	X 96
A	CHO	+ CH2O	= CH3O	+ CO	H TRANSFER	X 97
A 39.	CHO	+ CH3	= CH2	+ CH2O		X 98
A 40.	CHO	+ CH3	= CH4	+ CO		X 99
A	CHO	+ CH3O	= CH2O	+ CH2O	H TRANSFER	X100
A	CHO	+ CH3O	= CH4	+ CO2	H-O EXCHANGE	X101
A	CHO	+ CH4	= CH2	+ CH3O	H-O EXCHANGE	X102
A 41.	CHO	+ CH4	= CH2O	+ CH3		X103
A 42.	CHO	+ H	= CH2	+ O		X104
A 43.	CHO	+ H	= CH2O	+ M		X105
A 44.	CHO	+ H	= CO	+ H2		X106

MASTER LIST OF REACTIONS FOR 25 ALLOWED SPECIES

A	.	CHO	+	HN	=	CH ₂	+	NO	H-O EXCHANGE	X107
A	.	CHO	+	HN	=	CH ₂ O	+	N	H TRANSFER	X108
A	.	CHO	+	HN	=	CN	+	H ₂ O	N-(HO) EXCHANGE	X109
A	.	CHO	+	HNO	=	CH ₂	+	NO ₂	H-O EXCHANGE	X110
A 45.	.	CHO	+	HNO	=	CH ₂ O	+	NO		X111
A	.	CHO	+	HO	=	CH ₂	+	O ₂	H-O EXCHANGE	X112
A 46.	.	CHO	+	HO	=	CH ₂ O	+	O		X113
A 47.	.	CHO	+	HO	=	CO	+	H ₂ O		X114
A	.	CHO	+	HO	=	CO ₂	+	H ₂	H-O EXCHANGE	X115
A	.	CHO	+	HO?	=	CH ₂ O	+	O ₂	H TRANSFER	X116
A	.	CHO	+	HO?	=	CO ₂	+	H ₂ O	H-O EXCHANGE	X117
A	.	CHO	+	H ₂	=	CH ₂	+	HO	H-O EXCHANGE	X118
A 48.	.	CHO	+	H ₂	=	CH ₂ O	+	H		X119
A	.	CHO	+	H ₂	=	CH ₃	+	O	O-(H ₂) EXCHANGE	X120
A	.	CHO	+	H ₂	+ M	=	CH ₃ O	+ M	(H ₂) ADDITION	X121
A	.	CHO	+	H ₂ O	=	CH ₂	+	HO ₂	H-O EXCHANGE	X122
A 49.	.	CHO	+	H ₂ O	=	CH ₂ O	+	HO		X123
A	.	CHO	+	H ₂ O	=	CH ₃	+	O ₂	O-(H ₂) EXCHANGE	X124
A	.	CHO	+	H ₂ O	=	CH ₃ O	+	O	(H ₂) TRANSFER	X125
A	.	CHO	+	N	=	CN	+	HO	N-(HO) EXCHANGE	X126
A 50.	.	CHO	+	N	=	CO	+	HN		X127
A	.	CHO	+	NO	=	CN	+	HO ₂	N-(HO) EXCHANGE	X128
A 51.	.	CHO	+	NO	=	CO	+	HNO		X129
A	.	CHO	+	NO	=	CO ₂	+	HN	H-O EXCHANGE	X130
A	.	CHO	+	NO ₂	=	CO ₂	+	HNO	H-O EXCHANGE	X131
A	.	CHO	+	N ₂	=	CN	+	HNO	N-(HO) EXCHANGE	X132
A 52.	.	CHO	+	O	=	CO	+	HO		X133
A	.	CHO	+	O	=	CO ₂	+	H	H-O EXCHANGE	X134
A	.	CHO	+	O ₂	=	CO	+	HO ₂	H TRANSFER	X135
A	.	CHO	+	O ₂	=	CO ₂	+	HO	H-O EXCHANGE	X136
A	.	CH ₂	+	CH ₂ O	=	CH ₄	+	CO	(H ₂) TRANSFER	X137
A	.	CH ₂	+	CH ₃ O	=	CH ₂ O	+	CH ₃	H TRANSFER	X138
A 53.	.	CH ₂	+	CH ₄	=	CH ₃	+	CH ₃		X139
A	.	CH ₂	+	CO ₂	=	CH ₂ O	+	CO	O TRANSFER	X140
A	.	CH ₂	+	H	+ M	=	CH ₃	+ M	H ADDITION	X141
A	.	CH ₂	+	HN	=	CH ₃	+	N	H TRANSFER	X142
A	.	CH ₂	+	HNO	=	CH ₂ O	+	HN	O TRANSFER	X143
A 54.	.	CH ₂	+	HNO	=	CH ₃	+	NO		X144
A	.	CH ₂	+	HNO	=	CH ₃ O	+	N	(HO) TRANSFER	X145
A	.	CH ₂	+	HO	=	CH ₂ O	+	H	O TRANSFER	X146
A 55.	.	CH ₂	+	HO	=	CH ₃	+	O		X147
A	.	CH ₂	+	HO	+ M	=	CH ₃ O	+ M	(HO) ADDITION	X148
A	.	CH ₂	+	HO ₂	=	CH ₂ O	+	HO	O TRANSFER	X149
A	.	CH ₂	+	HO ₂	=	CH ₃	+	O ₂	H TRANSFER	X150
A	.	CH ₂	+	HO ₂	=	CH ₃ O	+	O	(HO) TRANSFER	X151
A 56.	.	CH ₂	+	H ₂	=	CH ₃	+	H		X152
A	.	CH ₂	+	H ₂	+ M	=	CH ₄	+ M	(H ₂) ADDITION	X153
A	.	CH ₂	+	H ₂ O	=	CH ₂ O	+	H ₂	O TRANSFER	X154
A 57.	.	CH ₂	+	H ₂ O	=	CH ₃	+	HO		X155
A	.	CH ₂	+	H ₂ O	=	CH ₃ O	+	H	(HO) TRANSFER	X156
A	.	CH ₂	+	H ₂ O	=	CH ₄	+	O	(H ₂) TRANSFER	X157
A	.	CH ₂	+	NO	=	CH ₂ O	+	N	O TRANSFER	X158
A	.	CH ₂	+	N	=	CN	+	H ₂	N-(H ₂) EXCHANGE	X159

MASTER LIST OF REACTIONS FOR 25 ALLOWED SPECIES

A	.	CH ₂	+	NO		=	CN	+	H ₂ O		N-(H ₂) EXCHANGE	X160
A	.	CH ₂	+	NO ₂		=	CH ₂ O	+	NO		O TRANSFER	X161
A	.	CH ₂	+	N ₂ O		=	CH ₂ O	+	N ₂		O TRANSFER	X162
A	.	CH ₂	+	O	+ M	=	CH ₂ O			+ M	O ADDITION	X163
A	.	CH ₂	+	O		=	CO	+	H ₂		O-(H ₂) EXCHANGE	X164
A 58.	.	CH ₂	+	O ₂		=	CH ₂ O	+	O			X165
A	.	CH ₂	+	O ₂		=	CO	+	H ₂ O		O-(H ₂) EXCHANGE	X166
A	.	CH ₂	+	O ₂		=	CO ₂	+	H ₂		C TRANSFER	X167
A	.	CH ₂ O			+ M	=	CO	+	H ₂	+ M	(H ₂) ELIMINATION	X168
A	.	CH ₂ O	+	CH ₂ O		=	CH ₄	+	CO ₂		(H ₂)-(O ₂) EXCHANGE	X169
A	.	CH ₂ O	+	CH ₄		=	CH ₃	+	CH ₃ O		H TRANSFER	X170
A 59.	.	CH ₂ O	+	H		=	CH ₃	+	O			X171
A991.	.	CH ₂ O	+	H	+ M	=	CH ₃ O			+ M	H ADDITION	X172
A	.	CH ₂ O	+	HN		=	CH ₃	+	NO		H-O EXCHANGE	X173
A	.	CH ₂ O	+	HN		=	CH ₃ O	+	N		H TRANSFER	X174
A	.	CH ₂ O	+	HNO		=	CH ₃	+	NO ₂		H-O EXCHANGE	X175
A	.	CH ₂ O	+	HNO		=	CH ₃ O	+	NO		H TRANSFER	X176
A 60.	.	CH ₂ O	+	HO		=	CH ₃	+	O ₂			X177
A	.	CH ₂ O	+	HO		=	CH ₃ O	+	O		H TRANSFER	X178
A	.	CH ₂ O	+	HO ₂		=	CH ₃ O	+	O ₂		H TRANSFER	X179
A	.	CH ₂ O	+	H ₂		=	CH ₃	+	HO		H-O EXCHANGE	X180
A	.	CH ₂ O	+	H ₂		=	CH ₃ O	+	H		H TRANSFER	X181
A	.	CH ₂ O	+	H ₂		=	CH ₄	+	O		O-(H ₂) EXCHANGE	X182
A	.	CH ₂ O	+	H ₂ O		=	CH ₃	+	HO ₂		H-O EXCHANGE	X183
A	.	CH ₂ O	+	H ₂ O		=	CH ₃ O	+	HO		H TRANSFER	X184
A	.	CH ₂ O	+	H ₂ O		=	CH ₄	+	O ₂		O-(H ₂) EXCHANGE	X185
A	.	CH ₂ O	+	N		=	CN	+	H ₂ O		C TRANSFER	X186
A	.	CH ₂ O	+	O		=	CO	+	H ₂ O		(H ₂) TRANSFER	X187
A	.	CH ₂ O	+	O		=	CO ₂	+	H ₂		O-(H ₂) EXCHANGE	X188
A	.	CH ₂ O	+	O ₂		=	CO ₂	+	H ₂ O		O-(H ₂) EXCHANGE	X189
A	.	CH ₃	+	CO ₂		=	CH ₃ O	+	CO		O TRANSFER	X190
A 61.	.	CH ₃	+	H	+ M	=	CH ₄			+ M		X191
A	.	CH ₃	+	HN		=	CH ₄	+	N		H TRANSFER	X192
A	.	CH ₃	+	HNO		=	CH ₃ O	+	HN		O TRANSFER	X193
A 62.	.	CH ₃	+	HNO		=	CH ₄	+	NO			X194
A	.	CH ₃	+	HO		=	CH ₃ O	+	H		O TRANSFER	X195
A 63.	.	CH ₃	+	HO		=	CH ₄	+	O			X196
A	.	CH ₃	+	HO ₂		=	CH ₃ O	+	HO		O TRANSFER	X197
A 64.	.	CH ₃	+	HO ₂		=	CH ₄	+	O ₂			X198
A 65.	.	CH ₃	+	H ₂		=	CH ₄	+	H			X199
A	.	CH ₃	+	H ₂ O		=	CH ₃ O	+	H ₂		O TRANSFER	X200
A 66.	.	CH ₃	+	H ₂ O		=	CH ₄	+	HO			X201
A	.	CH ₃	+	NO		=	CH ₃ O	+	N		O TRANSFER	X202
A	.	CH ₃	+	NO ₂		=	CH ₃ O	+	NO		O TRANSFER	X203
A	.	CH ₃	+	N ₂ O		=	CH ₃ O	+	N ₂		O TRANSFER	X204
A	.	CH ₃	+	O	+ M	=	CH ₃ O			+ M	O ADDITION	X205
A992.	.	CH ₃	+	O ₂		=	CH ₃ O	+	O		O TRANSFER	X206
A	.	CH ₃ O	+	H		=	CH ₄	+	O		H-O EXCHANGE	X207
A	.	CH ₃ O	+	HN		=	CH ₄	+	NO		H-O EXCHANGE	X208
A	.	CH ₃ O	+	HNO		=	CH ₄	+	NO ₂		H-O EXCHANGE	X209
A	.	CH ₃ O	+	HO		=	CH ₄	+	O ₂		H-O EXCHANGE	X210
A	.	CH ₃ O	+	H ₂		=	CH ₄	+	HO		H-O EXCHANGE	X211
A	.	CH ₃ O	+	H ₂ O		=	CH ₄	+	HO ₂		H-O EXCHANGE	X212

MASTER LIST OF REACTIONS FOR 25 ALLOWED SPECIES

A	.	CN	+	HO	=	CO	+	HN	N-O EXCHANGE	X213
A	.	CN	+	HO2	=	CO	+	HNO	N-O EXCHANGE	X214
A	.	CN	+	HO2	=	CO2	+	HN	C-H EXCHANGE	X215
A 67.	.	CN	+	NO	=	CO	+	N2		X216
A	.	CN	+	NO2	=	CO	+	N2O	N-O EXCHANGE	X217
A	.	CN	+	NO2	=	CO2	+	N2	C-N EXCHANGE	X218
A993.	.	CN	+	O	=	CO	+	N	N-O EXCHANGE	X219
A 68.	.	CN	+	O2	=	CO	+	NO		X220
A	.	CN	+	O2	=	CO2	+	N	C TRANSFER	X221
A 69.	.	CO	+	HNO	=	CO2	+	HN		X222
A 70.	.	CO	+	HO	=	CO2	+	H		X223
A 71.	.	CO	+	HO2	=	CO2	+	HO		X224
A 72.	.	CO	+	H2O	=	CO2	+	H2		X225
A 73.	.	CO	+	NO	=	CO2	+	N		X226
A 74.	.	CO	+	NO2	=	CO2	+	NO		X227
A 75.	.	CO	+	N2O	=	CO2	+	N2		X228
A 77.	.	CO	+	O	=	CO2				X229
A 78.	.	CO	+	O2	=	CO2	+	O		X230
A 79.	.	H	+	H	=	H2				X231
A 80.	.	H	+	HN	=	H2	+	N		X232
A 81.	.	H	+	HNO	=	HN	+	HO		X233
A 82.	.	H	+	HNO	=	H2	+	NO		X234
A	.	H	+	HNO	=	H2O	+	N	H-N EXCHANGE	X235
A 83.	.	H	+	HO	=	H2	+	O		X236
A 84.	.	H	+	HO	=	H2O				X237
A 85.	.	H	+	HO2	=	HO	+	HO		X238
A 86.	.	H	+	HO2	=	H2	+	O2		X239
A 87.	.	H	+	HO2	=	H2O	+	O		X240
A 88.	.	H	+	H2O	=	HO	+	H2		X241
A 89.	.	H	+	N	=	HN				X242
A 90.	.	H	+	NO	=	HN	+	O		X243
A 92.	.	H	+	NO	=	HNO				X244
A 91.	.	H	+	NO	=	HO	+	N		X245
A	.	H	+	NO2	=	HN	+	O2	N TRANSFER	X246
A 93.	.	H	+	NO2	=	HNO	+	O		X247
A 94.	.	H	+	NO2	=	HO	+	NO		X248
A	.	H	+	NO2	=	HO2	+	N	H-N EXCHANGE	X249
A 95.	.	H	+	N2	=	HN	+	N		X250
A 96.	.	H	+	N2O	=	HN	+	NO		X251
A 97.	.	H	+	N2O	=	HNO	+	N		X252
A 98.	.	H	+	N2O	=	HO	+	N2		X253
A 99.	.	H	+	O	=	HO				X254
A100.	.	H	+	O2	=	HO	+	O		X255
A101.	.	H	+	O2	=	HO2				X256
A102.	.	HN	+	HN	=	H2	+	N2		X257
A	.	HN	+	HNO	=	H2	+	N2O	H-N EXCHANGE	X258
A	.	HN	+	HNO	=	H2O	+	N2	H-N EXCHANGE	X259
A103.	.	HN	+	HO	=	H2	+	NO		X260
A104.	.	HN	+	HO	=	H2O	+	N		X261
A	.	HN	+	HO2	=	HNO	+	HO	O TRANSFER	X262
A	.	HN	+	HO2	=	H2	+	NO2	H-N EXCHANGE	X263
A	.	HN	+	HO2	=	H2O	+	NO	H-O EXCHANGE	X264
A	.	HN	+	H2O	=	HNO	+	H2	O TRANSFER	X265

MASTER LIST OF REACTIONS FOR 25 ALLOWED SPECIES

A105.	HN	+	NO	=	HNO	+	N			X266		
A	.	HN	+	NO	=	HO	+	N2	H-N EXCHANGE	X267		
A106.	HN	+	NO2	=	HNO	+	NO			X268		
A	.	HN	+	NO2	=	HO	+	N2O	N-O EXCHANGE	X269		
A	.	HN	+	NO2	=	HO2	+	N2	H-N EXCHANGE	X270		
A107.	HN	+	N2O	=	HNO	+	N2			X271		
A109.	HN	+	O	+	M	=	HNO		+	M	X272	
A108.	HN	+	O			=	HO	+	N		X273	
A110.	HN	+	O2			=	HNO	+	O		X274	
A	.	HN	+	O2		=	HO	+	NO	H-O EXCHANGE	X275	
A111.	HN	+	O2			=	HO2	+	N		X276	
A112.	HNO			+	M	=	HO	+	N	+	M	X277
A	.	HNO	+	HNO		=	H2O	+	N2O	H-N EXCHANGE	X278	
A	.	HNO	+	HO		=	H2	+	NO2	H-O EXCHANGE	X279	
A113.	HNO	+	HO			=	H2O	+	NO		X280	
A	.	HNO	+	HO2		=	H2O	+	NO2	H-O EXCHANGE	X281	
A	.	HNO	+	N		=	HO	+	N2	N TRANSFER	X282	
A114.	HNO	+	NO			=	HO	+	N2O		X283	
A	.	HNO	+	NO		=	HO2	+	N2	N-O EXCHANGE	X284	
A	.	HNO	+	NO2		=	HO2	+	N2O	H-N EXCHANGE	X285	
A115.	HNO	+	O			=	HO	+	NO		X286	
A	.	HNO	+	O		=	HO2	+	N	N-O EXCHANGE	X287	
A	.	HNO	+	O2		=	HO	+	NO2	H-O EXCHANGE	X288	
A	.	HNO	+	O2		=	HO2	+	NO	!! TRANSFER	X289	
A116.	HO	+	HO			=	H2	+	O2		X290	
A117.	HO	+	HO			=	H2O	+	O		X291	
A118.	HO	+	HO2			=	H2O	+	O2		X292	
A	.	HO	+	H2O		=	HO2	+	H2	H-O EXCHANGE	X293	
A119.	HO	+	NO			=	HO2	+	N		X294	
A120.	HO	+	NO2			=	HO2	+	NC		X295	
A	.	HO	+	N2O		=	HO2	+	N2	O TRANSFER	X296	
A121.	HO	+	O	+	M	=	HO2			+	M	X297
A122.	HO	+	O2			=	HO2	+	O			X298
A	.	H2	+	NO		=	H2O	+	N	O TRANSFER	X299	
A123.	H2	+	NO2			=	H2O	+	NO		X300	
A	.	H2	+	N2O		=	H2O	+	N2	O TRANSFER	X301	
A	.	H2	+	O	+	M	=	H2O		+	M	X302
A	.	H2	+	O2		=	H2O	+	O	(H2) ADDITION	X303	
A124.	N	+	N	+	M	=	N2			+	M	X304
A125.	N	+	NO			=	N2	+	O			X305
A126.	N	+	NO	+	M	=	N2O			+	M	X306
A127.	N	+	NO2			=	NO	+	NO			X307
A129.	N	+	NO2			=	N2	+	O2			X308
A130.	N	+	NO2			=	N2O	+	O			X309
A131.	N	+	N2O			=	NO	+	N2			X310
A132.	N	+	O	+	M	=	NO			+	M	X311
A133.	N	+	O2			=	NO	+	O			X312
A	.	N	+	O2	+	M	=	NO2		+	M	X313
A134.	NO	+	NO			=	N2	+	O2	N ADDITION	X314	
A135.	NO	+	NO			=	N2O	+	O			X315
A136.	NO	+	NO2			=	N2O	+	O2			X316
A137.	NO	+	N2O			=	NO2	+	N2			X317
A138.	NO	+	O	+	M	=	NO2			+	M	X318

MASTER LIST OF REACTIONS FOR 25 ALLOWED SPECIES

A139.	NO	+ O2		= NO2	+ O		X319
A140.	N2	+ O	+ M	= N2O		+ M	X320
A141.	N2	+ O2		= N2O	+ O		X321
A142.	O	+ O	+ M	= O2		+ M	X322

APPENDIX BCROSS-INDEX OF REACTIONS FOR 25 SPECIES

As an aid to seeking competitive reactions between the same species or reactions between a given species and competitive partners, a complete sorting of the reactions for each species is provided in this section. For example, if one were seeking reactions to break the $N\equiv N$ bond in molecular nitrogen, all the reactions of N_2 are listed together. If one were seeking reactions to produce N atoms, all the reactions involving N atoms are listed together. These lists are also useful in determining the probable relative importance of competing reactions as well as determining whether the relative rates used for competing reactions are reasonable.

The species covered in this Appendix are:

CH	HN
CHN	HNO
CHO	HO
CH ₂	HO ₂
CH ₂ O	H ₂
CH ₃	H ₂ O
CH ₃ O	N
CH ₄	NO
CN	NO ₂
CO	N ₂
CO ₂	N ₂ O
H	O
	O ₂

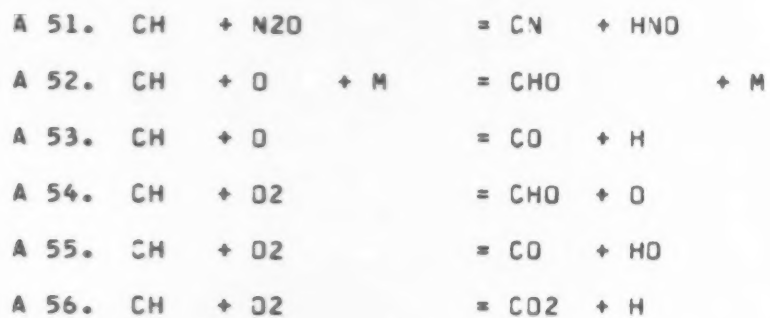
REACTIONS OF CH

A 1.	CH	+	CHN		=	CH2	+	CN	
A 2.	CH	+	CHO		=	CH2	+	CO	
A 3.	CH	+	CH2O		=	CHO	+	CH2	
A 4.	CH	+	CH2O		=	CH3	+	CO	
A 5.	CH	+	CH3		=	CH2	+	CH2	
A 6.	CH	+	CH3O		=	CHO	+	CH3	
A 7.	CH	+	CH3O		=	CH2	+	CH2O	
A 8.	CH	+	CH3O		=	CH4	+	CO	
A 9.	CH	+	CH4		=	CH2	+	CH3	
A 10.	CH	+	CO2		=	CHO	+	CO	
A 11.	CH	+	H	+	M	=	CH2	+	M
A 12.	CH	+	HN		=	CHN	+	H	
A 13.	CH	+	HN		=	CH2	+	N	
A 14.	CH	+	HN		=	CN	+	H2	
A 15.	CH	+	HNO		=	CHN	+	HO	
A 16.	CH	+	HNO		=	CHO	+	HN	
A 17.	CH	+	HNO		=	CH2	+	NO	
A 18.	CH	+	HNO		=	CH2O	+	N	
A 19.	CH	+	HNO		=	CN	+	H2O	
A 20.	CH	+	HO		=	CHO	+	H	
A 21.	CH	+	HO		=	CH2	+	O	
A 22.	CH	+	HO	+	M	=	CH2O	+	M
A 23.	CH	+	HO		=	CO	+	H2	
A 24.	CH	+	HO2		=	CHO	+	HO	
A 25.	CH	+	HO2		=	CH2	+	O2	

REACTIONS OF CH

A 26.	CH	+	HO2		=	CH2O	+	O	
A 27.	CH	+	HO2		=	CO	+	H2O	
A 28.	CH	+	HO2		=	CO2	+	H2	
A 29.	CH	+	H2		=	CH2	+	H	
A 30.	CH	+	H2	+	M	=	CH3	+	M
A 31.	CH	+	H2O		=	CHO	+	H2	
A 32.	CH	+	H2O		=	CH2	+	HO	
A 33.	CH	+	H2O		=	CH2O	+	H	
A 34.	CH	+	H2O		=	CH3	+	O	
A 35.	CH	+	H2O	+	M	=	CH3O	+	M
A 36.	CH	+	N	+	M	=	CHN	+	M
A 37.	CH	+	N		=	CN	+	H	
A 38.	CH	+	NO		=	CHN	+	O	
A 39.	CH	+	NO		=	CHO	+	N	
A 40.	CH	+	NO		=	CN	+	HO	
A 41.	CH	+	NO		=	CO	+	HN	
A 42.	CH	+	NO2		=	CHN	+	O2	
A 43.	CH	+	NO2		=	CHO	+	NO	
A 44.	CH	+	NO2		=	CN	+	HO2	
A 45.	CH	+	NO2		=	CO	+	HNO	
A 46.	CH	+	NO2		=	CO2	+	HN	
A 47.	CH	+	N2		=	CHN	+	N	
A 48.	CH	+	N2		=	CN	+	HN	
A 49.	CH	+	N2O		=	CHN	+	NO	
A 50.	CH	+	N2O		=	CHO	+	N2	

REACTIONS OF CH



REACTIONS OF CHN

C 36.	CHN	+ M	= CH	+ N	+ M
A 57.	CHN	+ M	= CN	+ H	+ M
B 1.	CHN + CH		= CH ₂	+ CN	
A 58.	CHN + CHO		= CH ₂ O	+ CN	
A 59.	CHN + CH ₂		= CH ₃	+ CN	
A 60.	CHN + CH ₂ O		= CH ₃ O	+ CN	
A 61.	CHN + CH ₃		= CH ₄	+ CN	
A 62.	CHN + CO		= CHO	+ CN	
C 12.	CHN + H		= CH	+ HN	
A 63.	CHN + H		= CH ₂	+ N	
A 64.	CHN + H		= CN	+ H ₂	
A 65.	CHN + HN		= CH ₂	+ N ₂	
A 66.	CHN + HNO		= CH ₂	+ N ₂ O	
A 67.	CHN + HNO		= CH ₂ O	+ N ₂	
C 15.	CHN + HO		= CH	+ HNO	
A 68.	CHN + HO		= CHO	+ HN	
A 69.	CHN + HO		= CH ₂	+ NO	
A 70.	CHN + HO		= CH ₂ O	+ N	
A 71.	CHN + HO		= CN	+ H ₂ O	
A 72.	CHN + HO ₂		= CHO	+ HNO	
A 73.	CHN + HO ₂		= CH ₂	+ NO ₂	
A 74.	CHN + HO ₂		= CH ₂ O	+ NO	
A 75.	CHN + H ₂		= CH ₂	+ H ₂ N	
A 76.	CHN + H ₂		= CH ₃	+ N	
A 77.	CHN + H ₂ O		= CH ₂	+ HNO	

REACTIONS OF CHN

A 78.	CHN + H ₂ O	= CH ₂ O + HN
A 79.	CHN + H ₂ O	= CH ₃ + NO
A 80.	CHN + H ₂ O	= CH ₃ O + N
C 47.	CHN + N	= CH + N ₂
A 81.	CHN + N	= CN + HN
C 49.	CHN + NO	= CH + N ₂ O
A 82.	CHN + NO	= CHO + N ₂
A 83.	CHN + NO	= CN + HNO
A 84.	CHN + NO ₂	= CHO + N ₂ O
C 38.	CHN + O	= CH + NO
A 85.	CHN + O	= CHO + N
A 86.	CHN + O	= CN + HO
A 87.	CHN + O	= CO + HN
C 42.	CHN + O ₂	= CH + NO ₂
A 88.	CHN + O ₂	= CHO + NO
A 89.	CHN + O ₂	= CN + HO ₂
A 90.	CHN + O ₂	= CO + HNO
A 91.	CHN + O ₂	= CO ₂ + HN

REACTIONS OF CHO

C 52.	CHO	+ M	= CH	+ O	+ M
A 92.	CHO	+ M	= CO	+ H	+ M
B 2.	CHO + CH		= CH ₂	+ CO	
B 58.	CHO + CHN		= CH ₂ O	+ CN	
A 93.	CHO + CHO		= CH ₂	+ CO ₂	
A 94.	CHO + CHO		= CH ₂ O	+ CO	
C 3.	CHO + CH ₂		= CH	+ CH ₂ O	
A 95.	CHO + CH ₂		= CH ₃	+ CO	
A 96.	CHO + CH ₂ O		= CH ₃	+ CO ₂	
A 97.	CHO + CH ₂ O		= CH ₃ O	+ CO	
C 6.	CHO + CH ₃		= CH	+ CH ₃ O	
A 98.	CHO + CH ₃		= CH ₂	+ CH ₂ O	
A 99.	CHO + CH ₃		= CH ₄	+ CO	
A100.	CHO + CH ₃ O		= CH ₂ O	+ CH ₂ O	
A101.	CHO + CH ₃ O		= CH ₄	+ CO ₂	
A102.	CHO + CH ₄		= CH ₂	+ CH ₃ O	
A103.	CHO + CH ₄		= CH ₂ O	+ CH ₃	
C 62.	CHO + CN		= CHN	+ CO	
C 10.	CHO + CO		= CH	+ CO ₂	
C 20.	CHO + H		= CH	+ HO	
A104.	CHO + H		= CH ₂	+ O	
A105.	CHO + H	+ M	= CH ₂ O		+ M
A106.	CHO + H		= CO	+ H ₂	
C 16.	CHO + HN		= CH	+ HNO	
C 68.	CHO + HN		= CHN	+ HO	

REACTIONS OF CHO

A107.	CHO	+	HN		=	CH2	+	NO	
A108.	CHO	+	HN		=	CH2O	+	N	
A109.	CHO	+	HN		=	CN	+	H2O	
C 72.	CHO	+	HNO		=	CHN	+	HO2	
A110.	CHO	+	HNO		=	CH2	+	NO2	
A111.	CHO	+	HNO		=	CH2O	+	NO	
C 24.	CHO	+	HO		=	CH	+	HO2	
A112.	CHO	+	HO		=	CH2	+	O2	
A113.	CHO	+	HO		=	CH2O	+	O	
A114.	CHO	+	HO		=	CO	+	H2O	
A115.	CHO	+	HO		=	CO2	+	H2	
A116.	CHO	+	HO2		=	CH2O	+	O2	
A117.	CHO	+	HO2		=	CO2	+	H2O	
C 31.	CHO	+	H2		=	CH	+	H2O	
A118.	CHO	+	H2		=	CH2	+	HO	
A119.	CHO	+	H2		=	CH2O	+	H	
A120.	CHO	+	H2		=	CH3	+	O	
A121.	CHO	+	H2	+	M	=	CH3O	+	M
A122.	CHO	+	H2O		=	CH2	+	HO2	
A123.	CHO	+	H2O		=	CH2O	+	HO	
A124.	CHO	+	H2O		=	CH3	+	O2	
A125.	CHO	+	H2O		=	CH3O	+	O	
C 39.	CHO	+	N		=	CH	+	NO	
C 85.	CHO	+	N		=	CHN	+	O	
A126.	CHO	+	N		=	CN	+	HO	

REACTIONS OF CHO

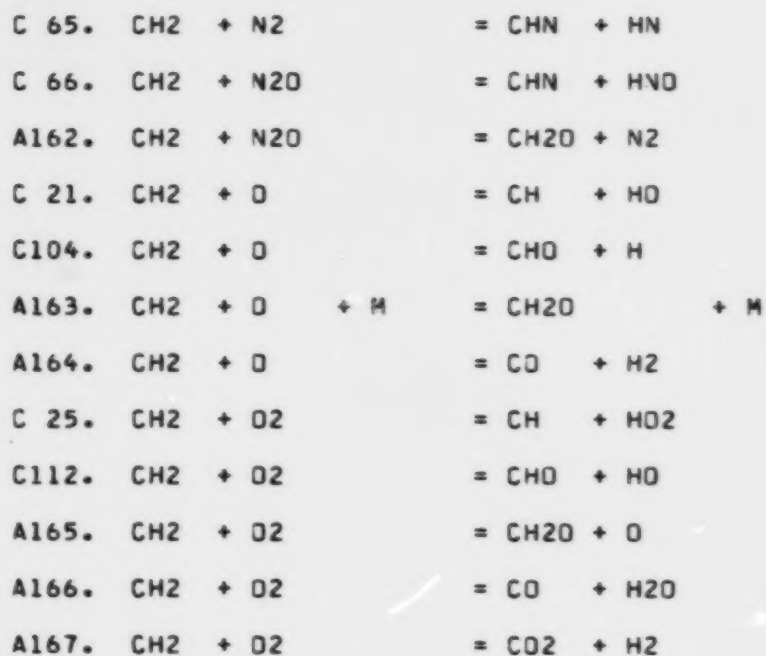
A127.	CHO	+	N	=	CO	+	HN
C 43.	CHO	+	NO	=	CH	+	NO2
C 88.	CHO	+	NO	=	CHN	+	O2
A128.	CHO	+	NO	=	CN	+	HO2
A129.	CHO	+	NO	=	CO	+	HNO
A130.	CHO	+	NO	=	CO2	+	HN
A131.	CHO	+	NO2	=	CO2	+	HNO
C 50.	CHO	+	N2	=	CH	+	N2O
C 82.	CHO	+	N2	=	CHN	+	NO
A132.	CHO	+	N2	=	CN	+	HNO
C 84.	CHO	+	N2O	=	CHN	+	NO2
C 54.	CHO	+	O	=	CH	+	O2
A133.	CHO	+	O	=	CO	+	HO
A134.	CHO	+	O	=	CO2	+	H
A135.	CHO	+	O2	=	CO	+	HO2
A136.	CHO	+	O2	=	CO2	+	HO

REACTIONS OF CH₂

C 11.	CH ₂	+ M	= CH + H + M
B 59.	CH ₂ + CHN		= CH ₃ + CN
D 3.	CH ₂ + CHO		= CH + CH ₂ O
B 95.	CH ₂ + CHO		= CH ₃ + CO
C 5.	CH ₂ + CH ₂		= CH + CH ₃
C 7.	CH ₂ + CH ₂ O		= CH + CH ₃ O
C 98.	CH ₂ + CH ₂ O		= CHO + CH ₃
A137.	CH ₂ + CH ₂ O		= CH ₄ + CO
C 9.	CH ₂ + CH ₃		= CH + CH ₄
C102.	CH ₂ + CH ₃ O		= CHO + CH ₄
A138.	CH ₂ + CH ₃ O		= CH ₂ O + CH ₃
A139.	CH ₂ + CH ₄		= CH ₃ + CH ₃
C 1.	CH ₂ + CN		= CH + CHN
C 2.	CH ₂ + CO		= CH + CHO
C 93.	CH ₂ + CO ₂		= CHO + CHO
A140.	CH ₂ + CO ₂		= CH ₂ O + CO
C 29.	CH ₂ + H		= CH + H ₂
A141.	CH ₂ + H + M		= CH ₃ + M
C 75.	CH ₂ + HN		= CHN + H ₂
A142.	CH ₂ + HN		= CH ₃ + N
C 77.	CH ₂ + HNO		= CHN + H ₂ O
A143.	CH ₂ + HNO		= CH ₂ O + HN
A144.	CH ₂ + HNO		= CH ₃ + NO
A145.	CH ₂ + HNO		= CH ₃ O + N
C 32.	CH ₂ + HO		= CH + H ₂ O

REACTIONS OF CH₂

C118.	CH2	+	HO		=	CHO	+	H2	
A146.	CH2	+	HO		=	CH2O	+	H	
A147.	CH2	+	HO		=	CH3	+	O	
A148.	CH2	+	HO	+	M	=	CH3O	+	M
C122.	CH2	+	HO2		=	CHO	+	H2O	
A149.	CH2	+	HO2		=	CH2O	+	HO	
A150.	CH2	+	HO2		=	CH3	+	O2	
A151.	CH2	+	HO2		=	CH3O	+	O	
A152.	CH2	+	H2		=	CH3	+	H	
A153.	CH2	+	H2	+	M	=	CH4	+	M
A154.	CH2	+	H2O		=	CH2O	+	H2	
A155.	CH2	+	H2O		=	CH3	+	HO	
A156.	CH2	+	H2O		=	CH3O	+	H	
A157.	CH2	+	H2O		=	CH4	+	O	
C 13.	CH2	+	N		=	CH	+	HN	
C 63.	CH2	+	N		=	CHN	+	H	
A158.	CH2	+	N		=	CN	+	H2	
C 17.	CH2	+	NO		=	CH	+	HNO	
C 69.	CH2	+	NO		=	CHN	+	HO	
C107.	CH2	+	NO		=	CHO	+	HN	
A159.	CH2	+	NO		=	CH2O	+	N	
A160.	CH2	+	NO		=	CN	+	H2O	
C 73.	CH2	+	NO2		=	CHN	+	HO2	
C110.	CH2	+	NO2		=	CHO	+	HNO	
A161.	CH2	+	NO2		=	CH2O	+	NO	

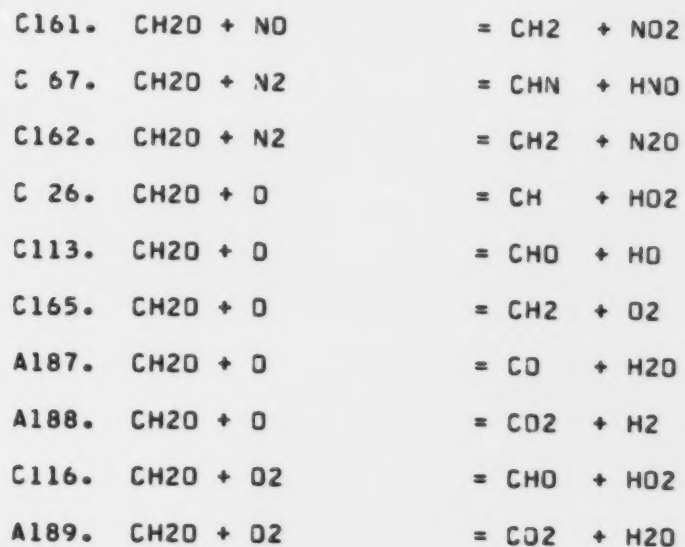
REACTIONS OF CH₂

REACTIONS OF CH₂O

C 22.	CH ₂ O	+ M	= CH + HO + M
C105.	CH ₂ O	+ M	= CHO + H + M
C163.	CH ₂ O	+ M	= CH ₂ + O + M
A168.	CH ₂ O	+ M	= CO + H ₂ + M
B 3.	CH ₂ O + CH		= CHO + CH ₂
B 4.	CH ₂ O + CH		= CH ₃ + CO
B 60.	CH ₂ O + CHN		= CH ₃ O + CN
B 96.	CH ₂ O + CHO		= CH ₃ + CO ₂
B 97.	CH ₂ O + CHO		= CH ₃ O + CO
D 7.	CH ₂ O + CH ₂		= CH + CH ₃ O
D 98.	CH ₂ O + CH ₂		= CHO + CH ₃
B137.	CH ₂ O + CH ₂		= CH ₄ + CO
C100.	CH ₂ O + CH ₂ O		= CHO + CH ₃ O
A169.	CH ₂ O + CH ₂ O		= CH ₄ + CO ₂
C103.	CH ₂ O + CH ₃		= CHO + CH ₄
C138.	CH ₂ O + CH ₃		= CH ₂ + CH ₃ O
A170.	CH ₂ O + CH ₄		= CH ₃ + CH ₃ O
C 58.	CH ₂ O + CN		= CHN + CHO
C 94.	CH ₂ O + CO		= CHO + CHO
C140.	CH ₂ O + CO		= CH ₂ + CO ₂
C 33.	CH ₂ O + H		= CH + H ₂ O
C119.	CH ₂ O + H		= CHO + H ₂
C146.	CH ₂ O + H		= CH ₂ + HO
A171.	CH ₂ O + H		= CH ₃ + O
A172.	CH ₂ O + H	+ M	= CH ₃ O + M

REACTIONS OF CH₂O

C 78.	CH ₂ O + HN	= CHN + H ₂ O
C143.	CH ₂ O + HN	= CH ₂ + HNO
A173.	CH ₂ O + HN	= CH ₃ + NO
A174.	CH ₂ O + HN	= CH ₃ O + N
A175.	CH ₂ O + HNO	= CH ₃ + NO ₂
A176.	CH ₂ O + HNO	= CH ₃ O + NO
C123.	CH ₂ O + HO	= CHO + H ₂ O
C149.	CH ₂ O + HO	= CH ₂ + HO ₂
A177.	CH ₂ O + HO	= CH ₃ + O ₂
A178.	CH ₂ O + HO	= CH ₃ O + O
A179.	CH ₂ O + HO ₂	= CH ₃ O + O ₂
C154.	CH ₂ O + H ₂	= CH ₂ + H ₂ O
A180.	CH ₂ O + H ₂	= CH ₃ + HO
A181.	CH ₂ O + H ₂	= CH ₃ O + H
A182.	CH ₂ O + H ₂	= CH ₄ + O
A183.	CH ₂ O + H ₂ O	= CH ₃ + HO ₂
A184.	CH ₂ O + H ₂ O	= CH ₃ O + HO
A185.	CH ₂ O + H ₂ O	= CH ₄ + O ₂
C 18.	CH ₂ O + N	= CH + HNO
C 70.	CH ₂ O + N	= CHN + HO
C108.	CH ₂ O + N	= CHO + HN
C159.	CH ₂ O + N	= CH ₂ + NO
A186.	CH ₂ O + N	= CN + H ₂ O
C 74.	CH ₂ O + NO	= CHN + HO ₂
C111.	CH ₂ O + NO	= CHO + HNO

REACTIONS OF CH₂O

REACTIONS OF CH₃

C 30.	CH ₃	+ M	= CH + H ₂ + M
C141.	CH ₃	+ M	= CH ₂ + H + M
B 5.	CH ₃ + CH		= CH ₂ + CH ₂
B 61.	CH ₃ + CHN		= CH ₄ + CN
D 6.	CH ₃ + CHO		= CH + CH ₃ O
B 98.	CH ₃ + CHO		= CH ₂ + CH ₂ O
B 99.	CH ₃ + CHO		= CH ₄ + CO
D 9.	CH ₃ + CH ₂		= CH + CH ₄
D103.	CH ₃ + CH ₂ O		= CHO + CH ₄
D138.	CH ₃ + CH ₂ O		= CH ₂ + CH ₃ O
C139.	CH ₃ + CH ₃		= CH ₂ + CH ₄
C170.	CH ₃ + CH ₃ O		= CH ₂ O + CH ₄
C 59.	CH ₃ + CN		= CHN + CH ₂
C 4.	CH ₃ + CO		= CH + CH ₂ O
C 95.	CH ₃ + CO		= CHO + CH ₂
C 96.	CH ₃ + CO ₂		= CHO + CH ₂ O
A190.	CH ₃ + CO ₂		= CH ₃ O + CO
C152.	CH ₃ + H		= CH ₂ + H ₂
A191.	CH ₃ + H + M		= CH ₄ + M
A192.	CH ₃ + HN		= CH ₄ + N
A193.	CH ₃ + HNO		= CH ₃ O + HN
A194.	CH ₃ + HNO		= CH ₄ + NO
C155.	CH ₃ + HO		= CH ₂ + H ₂ O
C180.	CH ₃ + HO		= CH ₂ O + H ₂
A195.	CH ₃ + HO		= CH ₃ O + H

REACTIONS OF CH₃

A196.	CH3	+	HO		=	CH4	+	O
C183.	CH3	+	HO2		=	CH2O	+	H2O
A197.	CH3	+	HO2		=	CH3O	+	HO
A198.	CH3	+	HO2		=	CH4	+	O2
A199.	CH3	+	H2		=	CH4	+	H
A200.	CH3	+	H2O		=	CH3O	+	H2
A201.	CH3	+	H2O		=	CH4	+	HO
C 76.	CH3	+	N		=	CHN	+	H2
C142.	CH3	+	N		=	CH2	+	HN
C 79.	CH3	+	NO		=	CHN	+	H2O
C144.	CH3	+	NO		=	CH2	+	HNO
C173.	CH3	+	NO		=	CH2O	+	HN
A202.	CH3	+	NO		=	CH3O	+	N
C175.	CH3	+	NO2		=	CH2O	+	HNO
A203.	CH3	+	NO2		=	CH3O	+	NO
A204.	CH3	+	N2O		=	CH3O	+	N2
C 34.	CH3	+	O		=	CH	+	H2O
C120.	CH3	+	O		=	CHO	+	H2
C147.	CH3	+	O		=	CH2	+	HO
C171.	CH3	+	O		=	CH2O	+	H
A205.	CH3	+	O	+ M	=	CH3O		+ M
C124.	CH3	+	O2		=	CHO	+	H2O
C150.	CH3	+	O2		=	CH2	+	HO2
C177.	CH3	+	O2		=	CH2O	+	HO
A206.	CH3	+	O2		=	CH3O	+	O

REACTIONS OF CH₃O

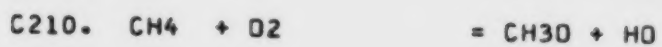
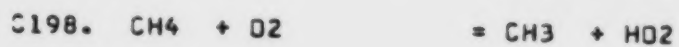
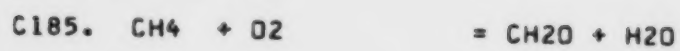
C 35.	CH ₃ O	+ M	= CH + H ₂ O + M
C121.	CH ₃ O	+ M	= CHO + H ₂ + M
C148.	CH ₃ O	+ M	= CH ₂ + HO + M
C172.	CH ₃ O	+ M	= CH ₂ O + H + M
C205.	CH ₃ O	+ M	= CH ₃ + O + M
B 6.	CH ₃ O + CH		= CHO + CH ₃
B 7.	CH ₃ O + CH		= CH ₂ + CH ₂ O
B 8.	CH ₃ O + CH		= CH ₄ + CO
B100.	CH ₃ O + CHO		= CH ₂ O + CH ₂ O
B101.	CH ₃ O + CHO		= CH ₄ + CO ₂
D102.	CH ₃ O + CH ₂		= CHO + CH ₄
B138.	CH ₃ O + CH ₂		= CH ₂ O + CH ₃
D170.	CH ₃ O + CH ₃		= CH ₂ O + CH ₄
C 60.	CH ₃ O + CN		= CHN + CH ₂ O
C 97.	CH ₃ O + CO		= CHO + CH ₂ O
C190.	CH ₃ O + CO		= CH ₃ + CO ₂
C156.	CH ₃ O + H		= CH ₂ + H ₂ O
C181.	CH ₃ O + H		= CH ₂ O + H ₂
C195.	CH ₃ O + H		= CH ₃ + HO
A207.	CH ₃ O + H		= CH ₄ + O
C193.	CH ₃ O + HN		= CH ₃ + HNO
A208.	CH ₃ O + HN		= CH ₄ + NO
A209.	CH ₃ O + HNO		= CH ₄ + NO ₂
C184.	CH ₃ O + HO		= CH ₂ O + H ₂ O
C197.	CH ₃ O + HO		= CH ₃ + HO ₂

REACTIONS OF CH₃O

A210.	CH ₃ O + HO	= CH ₄ + O ₂
C200.	CH ₃ O + H ₂	= CH ₃ + H ₂ O
A211.	CH ₃ O + H ₂	= CH ₄ + HO
A212.	CH ₃ O + H ₂ O	= CH ₄ + HO ₂
C 80.	CH ₃ O + N	= CHN + H ₂ O
C145.	CH ₃ O + N	= CH ₂ + HNO
C174.	CH ₃ O + N	= CH ₂ O + HN
C202.	CH ₃ O + N	= CH ₃ + NO
C176.	CH ₃ O + NO	= CH ₂ O + HNO
C203.	CH ₃ O + NO	= CH ₃ + NO ₂
C204.	CH ₃ O + N ₂	= CH ₃ + N ₂ O
C125.	CH ₃ O + O	= CHO + H ₂ O
C151.	CH ₃ O + O	= CH ₂ + HO ₂
C178.	CH ₃ O + O	= CH ₂ O + HO
C206.	CH ₃ O + O	= CH ₃ + O ₂
C179.	CH ₃ O + O ₂	= CH ₂ O + HO ₂

REACTIONS OF CH₄

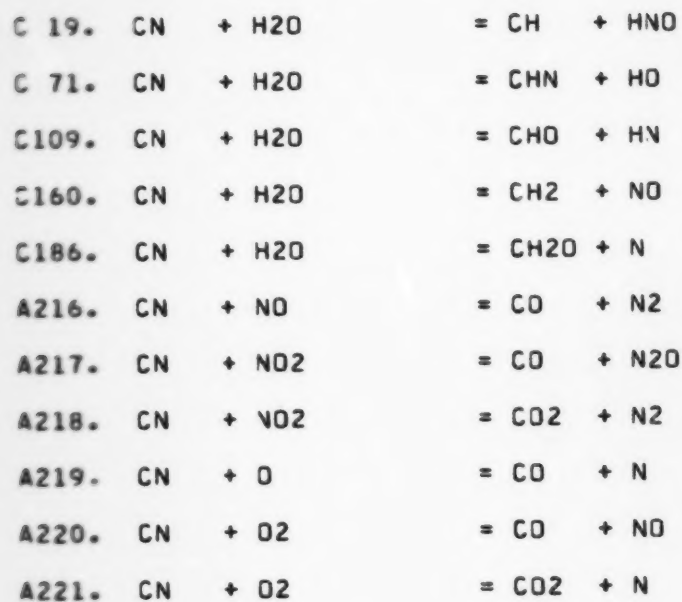
C153.	CH ₄	+ M	= CH ₂ + H ₂ + M
C191.	CH ₄	+ M	= CH ₃ + H + M
B 9.	CH ₄ + CH		= CH ₂ + CH ₃
B102.	CH ₄ + CHO		= CH ₂ + CH ₃ O
B103.	CH ₄ + CHO		= CH ₂ O + CH ₃
B139.	CH ₄ + CH ₂		= CH ₃ + CH ₃
B170.	CH ₄ + CH ₂ O		= CH ₃ + CH ₃ O
C 61.	CH ₄ + CN		= CHN + CH ₃
C 8.	CH ₄ + CO		= CH + CH ₃ O
C 99.	CH ₄ + CO		= CHO + CH ₃
C137.	CH ₄ + CO		= CH ₂ + CH ₂ O
C101.	CH ₄ + CO ₂		= CHO + CH ₃ O
C169.	CH ₄ + CO ₂		= CH ₂ O + CH ₂ O
C199.	CH ₄ + H		= CH ₃ + H ₂
C201.	CH ₄ + HO		= CH ₃ + H ₂ O
C211.	CH ₄ + HO		= CH ₃ O + H ₂
C212.	CH ₄ + HO ₂		= CH ₃ O + H ₂ O
C192.	CH ₄ + N		= CH ₃ + HN
C194.	CH ₄ + NO		= CH ₃ + HNO
C208.	CH ₄ + NO		= CH ₃ O + HN
C209.	CH ₄ + NO ₂		= CH ₃ O + HNO
C157.	CH ₄ + O		= CH ₂ + H ₂ O
C182.	CH ₄ + O		= CH ₂ O + H ₂
C196.	CH ₄ + O		= CH ₃ + HO
C207.	CH ₄ + O		= CH ₃ O + H

REACTIONS OF CH₄

REACTIONS OF CN

D 62.	CN	+ CHO	= CHN	+ CO
D 1.	CN	+ CH2	= CH	+ CHN
D 58.	CN	+ CH2O	= CHN	+ CHO
D 59.	CN	+ CH3	= CHN	+ CH2
D 60.	CN	+ CH3O	= CHN	+ CH2O
D 61.	CN	+ CH4	= CHN	+ CH3
C 37.	CN	+ H	= CH	+ N
C 57.	CN	+ H + M	= CHN	+ M
C 48.	CN	+ HN	= CH	+ N2
C 81.	CN	+ HN	= CHN	+ N
C 51.	CN	+ HNO	= CH	+ N2O
C 83.	CN	+ HNO	= CHN	+ NO
C132.	CN	+ HNO	= CHO	+ N2
C 40.	CN	+ HO	= CH	+ NO
C 86.	CN	+ HO	= CHN	+ O
C126.	CN	+ HO	= CHO	+ N
A213.	CN	+ HO	= CO	+ HN
C 44.	CN	+ HO2	= CH	+ NO2
C 89.	CN	+ HO2	= CHN	+ O2
C128.	CN	+ HO2	= CHO	+ NO
A214.	CN	+ HO2	= CO	+ HNO
A215.	CN	+ HO2	= CO2	+ HN
C 14.	CN	+ H2	= CH	+ HN
C 64.	CN	+ H2	= CHN	+ H
C158.	CN	+ H2	= CH2	+ N

REACTIONS OF CN



REACTIONS OF CO

B 62.	CO	+	CHN		=	CHO	+	CN	
D 10.	CO	+	CHO		=	CH	+	CO2	
D 2.	CO	+	CH2		=	CH	+	CHO	
D 94.	CO	+	CH2O		=	CHO	+	CHO	
D140.	CO	+	CH2O		=	CH2	+	CO2	
D 4.	CO	+	CH3		=	CH	+	CH2O	
D 95.	CO	+	CH3		=	CHO	+	CH2	
D 97.	CO	+	CH3O		=	CHO	+	CH2O	
D190.	CO	+	CH3O		=	CH3	+	CO2	
D 8.	CO	+	CH4		=	CH	+	CH3O	
D 99.	CO	+	CH4		=	CHO	+	CH3	
D137.	CO	+	CH4		=	CH2	+	CH2O	
C 53.	CO	+	H		=	CH	+	O	
C 92.	CO	+	H	+	M	=	CHO	+	M
C 41.	CO	+	HN		=	CH	+	NO	
C 87.	CO	+	HN		=	CHN	+	O	
C127.	CO	+	HN		=	CHO	+	N	
C213.	CO	+	HN		=	CN	+	HO	
C 45.	CO	+	HNO		=	CH	+	NO2	
C 90.	CO	+	HNO		=	CHN	+	O2	
C129.	CO	+	HNO		=	CHO	+	NO	
C214.	CO	+	HNO		=	CN	+	HO2	
A222.	CO	+	HNO		=	CO2	+	HN	
C 55.	CO	+	HO		=	CH	+	O2	
C133.	CO	+	HO		=	CHO	+	O	

REACTIONS OF CO

A223.	CO	+	HO		=	CO2	+	H		
C135.	CO	+	HO2		=	CHO	+	O2		
A224.	CO	+	HO2		=	CO2	+	HO		
C 23.	CO	+	H2		=	CH	+	HO		
C106.	CO	+	H2		=	CHO	+	H		
C164.	CO	+	H2		=	CH2	+	O		
C168.	CO	+	H2	+	M	=	CH2O		+	M
C 27.	CO	+	H2O		=	CH	+	HO2		
C114.	CO	+	H2O		=	CHO	+	HO		
C166.	CO	+	H2O		=	CH2	+	O2		
C187.	CO	+	H2O		=	CH2O	+	O		
A225.	CO	+	H2O		=	CO2	+	H2		
C219.	CO	+	N		=	CN	+	O		
C220.	CO	+	NO		=	CN	+	O2		
A226.	CO	+	NO		=	CO2	+	N		
A227.	CO	+	NO2		=	CO2	+	NO		
C216.	CO	+	N2		=	CN	+	NO		
C217.	CO	+	N2O		=	CN	+	NO2		
A228.	CO	+	N2O		=	CO2	+	N2		
A229.	CO	+	O	+	M	=	CO2		+	M
A230.	CO	+	O2		=	CO2	+	O		

REACTIONS OF CO₂

C229.	CO ₂	+ M	= CO + O + M
B 10.	CO ₂	+ CH	= CHO + CO
D 93.	CO ₂	+ CH ₂	= CHO + CHO
B140.	CO ₂	+ CH ₂	= CH ₂ O + CO
D 96.	CO ₂	+ CH ₃	= CHO + CH ₂ O
B190.	CO ₂	+ CH ₃	= CH ₃ O + CO
D101.	CO ₂	+ CH ₄	= CHO + CH ₃ O
D169.	CO ₂	+ CH ₄	= CH ₂ O + CH ₂ O
C 56.	CO ₂	+ H	= CH + O ₂
C134.	CO ₂	+ H	= CHO + O
C223.	CO ₂	+ H	= CO + HO
C 46.	CO ₂	+ HN	= CH + NO ₂
C 91.	CO ₂	+ HN	= CHN + O ₂
C130.	CO ₂	+ HN	= CHO + NO
C215.	CO ₂	+ HN	= CN + HO ₂
C222.	CO ₂	+ HN	= CO + HNO
C131.	CO ₂	+ HNC	= CHO + NO ₂
C136.	CO ₂	+ HO	= CHO + O ₂
C224.	CO ₂	+ HO	= CO + HO ₂
C 28.	CO ₂	+ H ₂	= CH + HO ₂
C115.	CO ₂	+ H ₂	= CHO + HO
C167.	CO ₂	+ H ₂	= CH ₂ + O ₂
C188.	CO ₂	+ H ₂	= CH ₂ O + O
C225.	CO ₂	+ H ₂	= CO + H ₂ O
C117.	CO ₂	+ H ₂ O	= CHO + HO ₂

REACTIONS OF CO₂

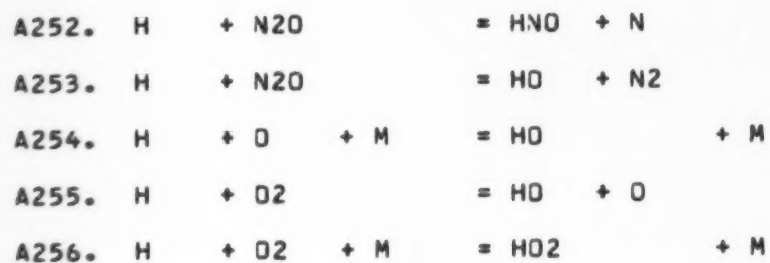
REACTIONS OF H

B 11.	H	+ CH	+ M	= CH ₂	+ M
D 12.	H	+ CHN		= CH	+ HN
B 63.	H	+ CHN		= CH ₂	+ N
B 64.	H	+ CHN		= CN	+ H ₂
D 20.	H	+ CHO		= CH	+ HO
B104.	H	+ CHO		= CH ₂	+ O
B105.	H	+ CHO	+ M	= CH ₂ O	+ M
B106.	H	+ CHO		= CO	+ H ₂
D 29.	H	+ CH ₂		= CH	+ H ₂
B141.	H	+ CH ₂	+ M	= CH ₃	+ M
D 33.	H	+ CH ₂ O		= CH	+ H ₂ O
D119.	H	+ CH ₂ O		= CH ₂	+ H ₂
D146.	H	+ CH ₂ O		= CH ₂	+ HO
B171.	H	+ CH ₂ O		= CH ₃	+ O
B172.	H	+ CH ₂ O	+ M	= CH ₃ O	+ M
D152.	H	+ CH ₃		= CH ₂	+ H ₂
B191.	H	+ CH ₃	+ M	= CH ₄	+ M
D156.	H	+ CH ₃ O		= CH ₂	+ H ₂ O
D181.	H	+ CH ₃ O		= CH ₂ O	+ H ₂
D195.	H	+ CH ₃ O		= CH ₃	+ HO
B207.	H	+ CH ₃ O		= CH ₄	+ O
D199.	H	+ CH ₄		= CH ₃	+ H ₂
D 37.	H	+ CN		= CH	+ N
D 57.	H	+ CN	+ M	= CHN	+ M
D 53.	H	+ CO		= CH	+ O

REACTIONS OF H

D 92.	H	+ CO	+ M	= CHO	+ M
D 56.	H	+ CO ₂		= CH + O ₂	
D134.	H	+ CO ₂		= CHO + O	
D223.	H	+ CO ₂		= CO + HO	
A231.	H	+ H	+ M	= H ₂	+ M
A232.	H	+ HN		= H ₂ + N	
A233.	H	+ HNO		= HN + HO	
A234.	H	+ HNO		= H ₂ + NO	
A235.	H	+ HNO		= H ₂ O + N	
A236.	H	+ HO		= H ₂ + O	
A237.	H	+ HO	+ M	= H ₂ O	+ M
A238.	H	+ HO ₂		= HO + HO	
A239.	H	+ HO ₂		= H ₂ + O ₂	
A240.	H	+ HO ₂		= H ₂ O + O	
A241.	H	+ H ₂ O		= HO + H ₂	
A242.	H	+ N	+ M	= HN	+ M
A243.	H	+ NO		= HN + O	
A244.	H	+ NO	+ M	= HNO	+ M
A245.	H	+ NO		= HO + N	
A246.	H	+ NO ₂		= HN + O ₂	
A247.	H	+ NO ₂		= HNO + O	
A248.	H	+ NO ₂		= HO + NO	
A249.	H	+ NO ₂		= HO ₂ + N	
A250.	H	+ N ₂		= HN + N	
A251.	H	+ N ₂ O		= HN + NO	

REACTIONS OF H



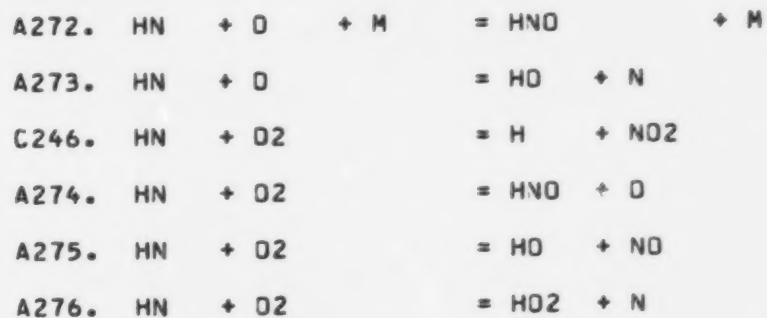
REACTIONS OF HN

C242.	HN		+ M	= H	+ N	+ M
B 12.	HN	+ CH		= CHN	+ H	
B 13.	HN	+ CH		= CH2	+ N	
B 14.	HN	+ CH		= CN	+ H2	
B 65.	HN	+ CHN		= CH2	+ N2	
D 16.	HN	+ CHO		= CH	+ HNO	
D 68.	HN	+ CHO		= CHN	+ HO	
B107.	HN	+ CHO		= CH2	+ NO	
B108.	HN	+ CHO		= CH2O	+ N	
B109.	HN	+ CHO		= CN	+ H2O	
D 75.	HN	+ CH2		= CHN	+ H2	
B142.	HN	+ CH2		= CH3	+ N	
D 78.	HN	+ CH2O		= CHN	+ H2O	
D143.	HN	+ CH2O		= CH2	+ HNO	
B173.	HN	+ CH2O		= CH3	+ NO	
B174.	HN	+ CH2O		= CH3O	+ N	
B192.	HN	+ CH3		= CH4	+ N	
D193.	HN	+ CH3O		= CH3	+ HNO	
B208.	HN	+ CH3O		= CH4	+ NO	
D 48.	HN	+ CN		= CH	+ N2	
D 81.	HN	+ CN		= CHN	+ N	
D 41.	HN	+ CO		= CH	+ NO	
D 87.	HN	+ CO		= CHN	+ O	
D127.	HN	+ CO		= CHO	+ N	
D213.	HN	+ CO		= CN	+ HO	

REACTIONS OF HN

D 46.	HN	+	CO ₂	=	CH	+	NO ₂
D 91.	HN	+	CO ₂	=	CHN	+	O ₂
D130.	HN	+	CO ₂	=	CHO	+	NO
D215.	HN	+	CO ₂	=	CN	+	HO ₂
D222.	HN	+	CO ₂	=	CO	+	HNO
B232.	HN	+	H	=	H ₂	+	N
A257.	HN	+	HN	=	H ₂	+	N ₂
A258.	HN	+	HNO	=	H ₂	+	N ₂ O
A259.	HN	+	HNO	=	H ₂ O	+	N ₂
C233.	HN	+	HO	=	H	+	HNO
A260.	HN	+	HO	=	H ₂	+	NO
A261.	HN	+	HO	=	H ₂ O	+	N
A262.	HN	+	HO ₂	=	HNO	+	HO
A263.	HN	+	HO ₂	=	H ₂	+	NO ₂
A264.	HN	+	HO ₂	=	H ₂ O	+	NO
A265.	HN	+	H ₂ O	=	HNO	+	H ₂
C250.	HN	+	N	=	H	+	N ₂
C251.	HN	+	NO	=	H	+	N ₂ O
A266.	HN	+	NO	=	HNO	+	N
A267.	HN	+	NO	=	HO	+	N ₂
A268.	HN	+	NO ₂	=	HNO	+	NO
A269.	HN	+	NO ₂	=	HO	+	N ₂ O
A270.	HN	+	NO ₂	=	HO ₂	+	N ₂
A271.	HN	+	N ₂ O	=	HNO	+	N ₂
C243.	HN	+	O	=	H	+	NO

REACTIONS OF HN



REACTIONS OF HNO

C244.	HNO	+ M	= H	+ NO	+ M
C272.	HNO	+ M	= HN	+ O	+ M
A277.	HNO	+ M	= HO	+ N	+ M
B 15.	HNO	+ CH	= CHN	+ HO	
B 16.	HNO	+ CH	= CHO	+ HN	
B 17.	HNO	+ CH	= CH ₂	+ NO	
B 18.	HNO	+ CH	= CH ₂ O	+ N	
B 19.	HNO	+ CH	= CN	+ H ₂ O	
B 66.	HNO	+ CHN	= CH ₂	+ N ₂ O	
B 67.	HNO	+ CHN	= CH ₂ O	+ N ₂	
D 72.	HNO	+ CHO	= CHN	+ HO ₂	
B110.	HNO	+ CHO	= CH ₂	+ NO ₂	
B111.	HNO	+ CHO	= CH ₂ O	+ NO	
D 77.	HNO	+ CH ₂	= CHN	+ H ₂ O	
B143.	HNO	+ CH ₂	= CH ₂ O	+ HN	
B144.	HNO	+ CH ₂	= CH ₃	+ NO	
B145.	HNO	+ CH ₂	= CH ₃ O	+ N	
B175.	HNO	+ CH ₂ O	= CH ₃	+ NO ₂	
B176.	HNO	+ CH ₂ O	= CH ₃ O	+ NO	
B193.	HNO	+ CH ₃	= CH ₃ O	+ HN	
B194.	HNO	+ CH ₃	= CH ₄	+ NO	
B209.	HNO	+ CH ₃ O	= CH ₄	+ NO ₂	
D 51.	HNO	+ CN	= CH	+ N ₂ O	
D 83.	HNO	+ CN	= CHN	+ NO	
D132.	HNO	+ CN	= CHO	+ N ₂	

REACTIONS OF HNO

D 45.	HNO + CO	= CH + NO ₂
D 90.	HNO + CO	= CHN + O ₂
D129.	HNO + CO	= CHO + NO
D214.	HNO + CO	= CN + HO ₂
B222.	HNO + CO	= CO ₂ + HN
D131.	HNO + CO ₂	= CHO + NO ₂
B233.	HNO + H	= HN + HO
B234.	HNO + H	= H ₂ + NO
B235.	HNO + H	= H ₂ O + N
B258.	HNO + HN	= H ₂ + N ₂ O
B259.	HNO + HN	= H ₂ O + N ₂
A278.	HNO + HNO	= H ₂ O + N ₂ O
C262.	HNO + HO	= HN + HO ₂
A279.	HNO + HO	= H ₂ + NO ₂
A280.	HNO + HO	= H ₂ O + NO
A281.	HNO + HO ₂	= H ₂ O + NO ₂
C265.	HNO + H ₂	= HN + H ₂ O
C252.	HNO + N	= H + N ₂ O
C266.	HNO + N	= HN + NO
A282.	HNO + N	= HO + N ₂
C268.	HNO + NO	= HN + NO ₂
A283.	HNO + NO	= HO + N ₂ O
A284.	HNO + NO	= HO ₂ + N ₂
A285.	HNO + NO ₂	= HO ₂ + N ₂ O
C271.	HNO + N ₂	= HN + N ₂ O

REACTIONS OF HNO

C247.	HNO	+	O	=	H	+	NO2
C274.	HNO	+	O	=	HN	+	O2
A286.	HNO	+	O	=	HO	+	NO
A287.	HNO	+	O	=	HO2	+	N
A288.	HNO	+	O2	=	HO	+	NO2
A289.	HNO	+	O2	=	HO2	+	NO

REACTIONS OF HO

C254.	HO		+ M	= H	+ O	+ M
B 20.	HO	+ CH		= CHO	+ H	
B 21.	HO	+ CH		= CH ₂	+ O	
B 22.	HO	+ CH	+ M	= CH ₂ O		+ M
B 23.	HO	+ CH		= CO	+ H ₂	
D 15.	HO	+ CHN		= CH	+ HNO	
B 68.	HO	+ CHN		= CHO	+ HN	
B 69.	HO	+ CHN		= CH ₂	+ NO	
B 70.	HO	+ CHN		= CH ₂ O	+ N	
B 71.	HO	+ CHN		= CN	+ H ₂ O	
D 24.	HO	+ CHO		= CH	+ HO ₂	
B112.	HO	+ CHO		= CH ₂	+ O ₂	
B113.	HO	+ CHO		= CH ₂ O	+ O	
B114.	HO	+ CHO		= CO	+ H ₂ O	
B115.	HO	+ CHO		= CO ₂	+ H ₂	
D 32.	HO	+ CH ₂		= CH	+ H ₂ O	
D118.	HO	+ CH ₂		= CHO	+ H ₂	
B146.	HO	+ CH ₂		= CH ₂ O	+ H	
B147.	HO	+ CH ₂		= CH ₃	+ O	
B148.	HO	+ CH ₂	+ M	= CH ₃ O		+ M
D123.	HO	+ CH ₂ O		= CHO	+ H ₂ O	
D149.	HO	+ CH ₂ O		= CH ₂	+ HO ₂	
B177.	HO	+ CH ₂ O		= CH ₃	+ O ₂	
B178.	HO	+ CH ₂ O		= CH ₃ O	+ O	
D155.	HO	+ CH ₃		= CH ₂	+ H ₂ O	

REACTIONS OF HO

D180.	HO	+ CH ₃	= CH ₂ O + H ₂
B195.	HO	+ CH ₃	= CH ₃ O + H
B196.	HO	+ CH ₃	= CH ₄ + O
D184.	HO	+ CH ₃ O	= CH ₂ O + H ₂ O
D197.	HO	+ CH ₃ O	= CH ₃ + HO ₂
B210.	HO	+ CH ₃ O	= CH ₄ + O ₂
D201.	HO	+ CH ₄	= CH ₃ + H ₂ O
D211.	HO	+ CH ₄	= CH ₃ O + H ₂
D 40.	HO	+ CN	= CH + NO
D 86.	HO	+ CN	= CHN + O
D126.	HO	+ CN	= CHO + N
B213.	HO	+ CN	= CO + HN
D 55.	HO	+ CO	= CH + O ₂
D133.	HO	+ CO	= CHO + O
B223.	HO	+ CO	= CO ₂ + H
D136.	HO	+ CO ₂	= CHO + O ₂
D224.	HO	+ CO ₂	= CO + HO ₂
B236.	HO	+ H	= H ₂ + O
B237.	HO	+ H + M	= H ₂ O + M
D233.	HO	+ HN	= H + HNO
B260.	HO	+ HN	= H ₂ + NO
B261.	HO	+ HN	= H ₂ O + N
D262.	HO	+ HNO	= HN + HO ₂
B279.	HO	+ HNO	= H ₂ + NO ₂
B280.	HO	+ HNO	= H ₂ O + NO

REACTIONS OF HO

C238.	HO	+	HO			=	H	+	HO2		
A290.	HO	+	HO			=	H2	+	O2		
A291.	HO	+	HO			=	H2O	+	O		
A292.	HO	+	HO2			=	H2O	+	O2		
C241.	HO	+	H2			=	H	+	H2O		
A293.	HO	+	H2O			=	HO2	+	H2		
C245.	HO	+	N			=	H	+	NO		
C273.	HO	+	N			=	HN	+	O		
C277.	HO	+	N	+	M	=	HNO			+	M
C248.	HO	+	NO			=	H	+	NO2		
C275.	HO	+	NO			=	HN	+	O2		
C286.	HO	+	NO			=	HNO	+	O		
A294.	HO	+	NO			=	HO2	+	N		
C288.	HO	+	NO2			=	HNO	+	O2		
A295.	HO	+	NO2			=	HO2	+	NO		
C253.	HO	+	N2			=	H	+	N2O		
C267.	HO	+	N2			=	HN	+	NO		
C282.	HO	+	N2			=	HNO	+	N		
C269.	HO	+	N2O			=	HN	+	NO2		
C283.	HO	+	N2O			=	HNO	+	NO		
A296.	HO	+	N2O			=	HO2	+	N2		
C255.	HO	+	O			=	H	+	O2		
A297.	HO	+	O	+	M	=	HO2			+	M
A298.	HO	+	O2			=	HO2	+	O		

REACTIONS OF HO₂

C256.	HO ₂	+ M	= H	+ O ₂	+ M
C297.	HO ₂	+ M	= HO	+ O	+ M
B 24.	HO ₂ + CH		= CHO	+ HO	
B 25.	HO ₂ + CH		= CH ₂	+ O ₂	
B 26.	HO ₂ + CH		= CH ₂ O	+ O	
B 27.	HO ₂ + CH		= CO	+ H ₂ O	
B 28.	HO ₂ + CH		= CO ₂	+ H ₂	
B 72.	HO ₂ + CHN		= CHO	+ HNO	
B 73.	HO ₂ + CHN		= CH ₂	+ NO ₂	
B 74.	HO ₂ + CHN		= CH ₂ O	+ NO	
B116.	HO ₂ + CHO		= CH ₂ O	+ O ₂	
B117.	HO ₂ + CHO		= CO ₂	+ H ₂ O	
D122.	HO ₂ + CH ₂		= CHO	+ H ₂ O	
B149.	HO ₂ + CH ₂		= CH ₂ O	+ HO	
B150.	HO ₂ + CH ₂		= CH ₃	+ O ₂	
B151.	HO ₂ + CH ₂		= CH ₃ O	+ O	
B179.	HO ₂ + CH ₂ O		= CH ₃ O	+ O ₂	
D183.	HO ₂ + CH ₃		= CH ₂ O	+ H ₂ O	
B197.	HO ₂ + CH ₃		= CH ₃ O	+ HO	
B198.	HO ₂ + CH ₃		= CH ₄	+ O ₂	
D212.	HO ₂ + CH ₄		= CH ₃ O	+ H ₂ O	
D 44.	HO ₂ + CN		= CH	+ NO ₂	
D 89.	HO ₂ + CN		= CHN	+ O ₂	
D128.	HO ₂ + CN		= CHO	+ NO	
B214.	HO ₂ + CN		= CO	+ HNO	

REACTIONS OF HO₂

B215.	HO ₂	+	CN	=	CO ₂	+	HN
D135.	HO ₂	+	CO	=	CHO	+	O ₂
B224.	HO ₂	+	CO	=	CO ₂	+	HO
B238.	HO ₂	+	H	=	HO	+	HO
B239.	HO ₂	+	H	=	H ₂	+	O ₂
B240.	HO ₂	+	H	=	H ₂ O	+	O
B262.	HO ₂	+	HN	=	HNO	+	HO
B263.	HO ₂	+	HN	=	H ₂	+	NO ₂
B264.	HO ₂	+	HN	=	H ₂ O	+	NO
B281.	HO ₂	+	HNO	=	H ₂ O	+	NO ₂
B292.	HO ₂	+	HO	=	H ₂ O	+	O ₂
C293.	HO ₂	+	H ₂	=	HO	+	H ₂ O
C249.	HO ₂	+	N	=	H	+	NO ₂
C276.	HO ₂	+	N	=	HN	+	O ₂
C287.	HO ₂	+	N	=	HNO	+	O
C294.	HO ₂	+	N	=	HO	+	NO
C289.	HO ₂	+	NO	=	HNO	+	O ₂
C295.	HO ₂	+	NO	=	HO	+	NO ₂
C270.	HO ₂	+	N ₂	=	HN	+	NO ₂
C284.	HO ₂	+	N ₂	=	HNO	+	NO
C296.	HO ₂	+	N ₂	=	HO	+	N ₂ O
C285.	HO ₂	+	N ₂ O	=	HNO	+	NO ₂
C298.	HO ₂	+	O	=	HO	+	O ₂

REACTIONS OF H₂

C231.	H ₂		+ M	= H	+ H	+ M
B 29.	H ₂	+ CH		= CH ₂	+ H	
B 30.	H ₂	+ CH	+ M	= CH ₃		+ M
B 75.	H ₂	+ CHN		= CH ₂	+ HN	
B 76.	H ₂	+ CHN		= CH ₃	+ N	
D 31.	H ₂	+ CHO		= CH	+ H ₂ O	
B118.	H ₂	+ CHO		= CH ₂	+ HO	
B119.	H ₂	+ CHO		= CH ₂ O	+ H	
B120.	H ₂	+ CHO		= CH ₃	+ O	
B121.	H ₂	+ CHO	+ M	= CH ₃ O		+ M
B152.	H ₂	+ CH ₂		= CH ₃	+ H	
B153.	H ₂	+ CH ₂	+ M	= CH ₄		+ M
D154.	H ₂	+ CH ₂ O		= CH ₂	+ H ₂ O	
B180.	H ₂	+ CH ₂ O		= CH ₃	+ HO	
B181.	H ₂	+ CH ₂ O		= CH ₃ O	+ H	
B182.	H ₂	+ CH ₂ O		= CH ₄	+ O	
B199.	H ₂	+ CH ₃		= CH ₄	+ H	
D200.	H ₂	+ CH ₃ O		= CH ₃	+ H ₂ O	
B211.	H ₂	+ CH ₃ O		= CH ₄	+ HO	
D 14.	H ₂	+ CN		= CH	+ HN	
D 64.	H ₂	+ CN		= CHN	+ H	
D158.	H ₂	+ CN		= CH ₂	+ N	
D 23.	H ₂	+ CO		= CH	+ HO	
D106.	H ₂	+ CO		= CHO	+ H	
D164.	H ₂	+ CO		= CH ₂	+ O	

REACTIONS OF H₂

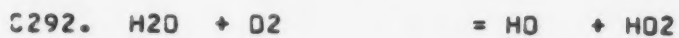
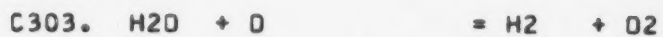
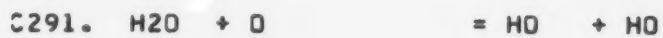
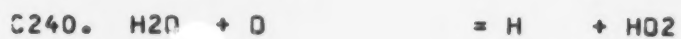
D168.	H ₂	+ CO	+ M	= CH ₂ O	+ M
D 28.	H ₂	+ CO ₂		= CH	+ HO ₂
D115.	H ₂	+ CO ₂		= CHO	+ HO
D167.	H ₂	+ CO ₂		= CH ₂	+ O ₂
D188.	H ₂	+ CO ₂		= CH ₂ O	+ O
D225.	H ₂	+ CO ₂		= CO	+ H ₂ O
D265.	H ₂	+ HNO		= HN	+ H ₂ O
D241.	H ₂	+ HO		= H	+ H ₂ O
D293.	H ₂	+ HO ₂		= HO	+ H ₂ O
C232.	H ₂	+ N		= H	+ HN
C234.	H ₂	+ NO		= H	+ HNO
C260.	H ₂	+ NO		= HN	+ HO
A299.	H ₂	+ NO		= H ₂ O	+ N
C263.	H ₂	+ NO ₂		= HN	+ HO ₂
C279.	H ₂	+ NO ₂		= HNO	+ HO
A300.	H ₂	+ NO ₂		= H ₂ O	+ NO
C257.	H ₂	+ N ₂		= HN	+ HN
C258.	H ₂	+ N ₂ O		= HN	+ HNO
A301.	H ₂	+ N ₂ O		= H ₂ O	+ N ₂
C236.	H ₂	+ O		= H	+ HO
A302.	H ₂	+ O	+ M	= H ₂ O	+ M
C239.	H ₂	+ O ₂		= H	+ HO ₂
C290.	H ₂	+ O ₂		= HO	+ HO
A303.	H ₂	+ O ₂		= H ₂ O	+ O

REACTIONS OF H₂O

C237.	H ₂ O	+ M	= H	+ HO	+ M
C302.	H ₂ O	+ M	= H ₂	+ O	+ M
B 31.	H ₂ O	+ CH	= CHO	+ H ₂	
B 32.	H ₂ O	+ CH	= CH ₂	+ HO	
B 33.	H ₂ O	+ CH	= CH ₂ O	+ H	
B 34.	H ₂ O	+ CH	= CH ₃	+ O	
B 35.	H ₂ O	+ CH	+ M	= CH ₃ O	+ M
B 77.	H ₂ O	+ CHN	= CH ₂	+ HNO	
B 78.	H ₂ O	+ CHN	= CH ₂ O	+ HN	
B 79.	H ₂ O	+ CHN	= CH ₃	+ NO	
B 80.	H ₂ O	+ CHN	= CH ₃ O	+ N	
B122.	H ₂ O	+ CHO	= CH ₂	+ HO ₂	
B123.	H ₂ O	+ CHO	= CH ₂ O	+ HO	
B124.	H ₂ O	+ CHO	= CH ₃	+ O ₂	
B125.	H ₂ O	+ CHO	= CH ₃ O	+ O	
B154.	H ₂ O	+ CH ₂	= CH ₂ O	+ H ₂	
B155.	H ₂ O	+ CH ₂	= CH ₃	+ HO	
B156.	H ₂ O	+ CH ₂	= CH ₃ O	+ H	
B157.	H ₂ O	+ CH ₂	= CH ₄	+ O	
B183.	H ₂ O	+ CH ₂ O	= CH ₃	+ HO ₂	
B184.	H ₂ O	+ CH ₂ O	= CH ₃ O	+ HO	
B185.	H ₂ O	+ CH ₂ O	= CH ₄	+ O ₂	
B200.	H ₂ O	+ CH ₃	= CH ₃ O	+ H ₂	
B201.	H ₂ O	+ CH ₃	= CH ₄	+ HO	
B212.	H ₂ O	+ CH ₃ O	= CH ₄	+ HO ₂	

REACTIONS OF H₂O

D 19.	H ₂ O + CN	= CH + HNO
D 71.	H ₂ O + CN	= CHN + HO
D109.	H ₂ O + CN	= CHO + HN
D160.	H ₂ O + CN	= CH ₂ + NO
D186.	H ₂ O + CN	= CH ₂ O + N
D 27.	H ₂ O + CO	= CH + HO ₂
D114.	H ₂ O + CO	= CHO + HO
D166.	H ₂ O + CO	= CH ₂ + O ₂
D187.	H ₂ O + CO	= CH ₂ O + O
B225.	H ₂ O + CO	= CO ₂ + H ₂
D117.	H ₂ O + CO ₂	= CHO + HO ₂
D189.	H ₂ O + CO ₂	= CH ₂ O + O ₂
B241.	H ₂ O + H	= HO + H ₂
B265.	H ₂ O + HN	= HNO + H ₂
B293.	H ₂ O + HO	= HO ₂ + H ₂
C235.	H ₂ O + N	= H + HNO
C261.	H ₂ O + N	= HN + HO
C299.	H ₂ O + N	= H ₂ + NO
C264.	H ₂ O + NO	= HN + HO ₂
C280.	H ₂ O + NO	= HNO + HO
C300.	H ₂ O + NO	= H ₂ + NO ₂
C281.	H ₂ O + NO ₂	= HNO + HO ₂
C259.	H ₂ O + N ₂	= HN + HNO
C301.	H ₂ O + N ₂	= H ₂ + N ₂ O
C278.	H ₂ O + N ₂ O	= HNO + HNO

REACTIONS OF H₂O

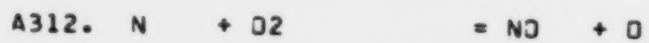
REACTIONS OF I

B 36.	N	+ CH	+ M	= CHN	+ M
B 37.	N	+ CH		= CN	+ H
D 47.	N	+ CHN		= CH	+ N2
B 81.	N	+ CHN		= CN	+ HN
D 39.	N	+ CHO		= CH	+ NO
D 85.	N	+ CHO		= CHN	+ O
B126.	N	+ CHO		= CN	+ HO
B127.	N	+ CHO		= CO	+ HN
D 13.	N	+ CH2		= CH	+ HN
D 63.	N	+ CH2		= CHN	+ H
B158.	N	+ CH2		= CN	+ H2
D 18.	N	+ CH2O		= CH	+ HNO
D 70.	N	+ CH2O		= CHN	+ HO
D108.	N	+ CH2O		= CHO	+ HN
D159.	N	+ CH2O		= CH2	+ NO
B186.	N	+ CH2O		= CN	+ H2O
D 76.	N	+ CH3		= CHN	+ H2
D142.	N	+ CH3		= CH2	+ HV
D 80.	N	+ CH3O		= CHN	+ H2O
D145.	N	+ CH3O		= CH2	+ HNO
D174.	N	+ CH3O		= CH2O	+ HN
D202.	N	+ CH3O		= CH3	+ NO
D192.	N	+ CH4		= CH3	+ HV
D219.	N	+ CO		= CN	+ O
D221.	N	+ CO2		= CN	+ O2

REACTIONS OF V

D226.	N	+ CO2		= CO	+ NO	
B242.	N	+ H	+ M	= HN		+ M
D250.	N	+ HN		= H	+ N2	
D252.	N	+ HNO		= H	+ N2O	
D266.	N	+ HNO		= HN	+ NO	
B282.	N	+ HNO		= HO	+ N2	
D245.	N	+ HO		= H	+ NO	
D273.	N	+ HO		= HN	+ O	
D277.	N	+ HO	+ M	= HNO		+ M
D249.	N	+ HO2		= H	+ NO2	
D276.	N	+ HO2		= HN	+ O2	
D287.	N	+ HO2		= HNO	+ O	
D294.	N	+ HO2		= HO	+ NO	
D232.	N	+ H2		= H	+ HN	
D235.	N	+ H2O		= H	+ HVO	
D261.	N	+ H2O		= HN	+ HO	
D299.	N	+ H2O		= H2	+ NO	
A304.	N	+ N	+ M	= N2		+ M
A305.	N	+ NO		= N2	+ O	
A306.	N	+ NO	+ M	= N2O		+ M
A307.	N	+ NO2		= NO	+ NO	
A308.	N	+ VO2		= N2	+ O2	
A309.	N	+ NO2		= N2O	+ O	
A310.	N	+ N2O		= NO	+ N2	
A311.	N	+ O	+ M	= NO		+ M

REACTIONS OF N



REACTIONS OF NO

C311.	NO	+ M	= N	+ O	+ M
B 38.	NO	+ CH	= CHN	+ O	
B 39.	NO	+ CH	= CHO	+ N	
B 40.	NO	+ CH	= CN	+ HO	
B 41.	NO	+ CH	= CO	+ HN	
D 49.	NO	+ CHN	= CH	+ N ₂ O	
B 82.	NO	+ CHN	= CHO	+ N ₂	
B 83.	NO	+ CHN	= CN	+ HNO	
D 43.	NO	+ CHO	= CH	+ NO ₂	
D 88.	NO	+ CHO	= CHN	+ O ₂	
B128.	NO	+ CHO	= CN	+ HO ₂	
B129.	NO	+ CHO	= CO	+ HNO	
B130.	NO	+ CHO	= CO ₂	+ HN	
D 17.	NO	+ CH ₂	= CH	+ HNO	
D 69.	NO	+ CH ₂	= CHN	+ HO	
D107.	NO	+ CH ₂	= CHO	+ HN	
B159.	NO	+ CH ₂	= CH ₂ O	+ N	
B160.	NO	+ CH ₂	= CN	+ H ₂ O	
D 74.	NO	+ CH ₂ O	= CHN	+ HO ₂	
D111.	NO	+ CH ₂ O	= CHO	+ HNO	
D161.	NO	+ CH ₂ O	= CH ₂	+ NO ₂	
D 79.	NO	+ CH ₃	= CHN	+ H ₂ O	
D144.	NO	+ CH ₃	= CH ₂	+ HNO	
D173.	NO	+ CH ₃	= CH ₂ O	+ HN	
B202.	NO	+ CH ₃	= CH ₃ O	+ N	

REACTIONS OF NO

D176.	NO	+ CH ₃ O		= CH ₂ O + HNO
D203.	NO	+ CH ₃ O		= CH ₃ + NO ₂
D194.	NO	+ CH ₄		= CH ₃ + HNO
D208.	NO	+ CH ₄		= CH ₃ O + H ₂
B216.	NO	+ CN		= CO + N ₂
D220.	NO	+ CO		= CN + O ₂
B226.	NO	+ CO		= CO ₂ + N
D227.	NO	+ CO ₂		= CO + NO ₂
B243.	NO	+ H		= HN + O
B244.	NO	+ H	+ M	= HNO + M
B245.	NO	+ H		= HO + N
D251.	NO	+ HN		= H + N ₂ O
B266.	NO	+ HN		= HNO + N
B267.	NO	+ HN		= HO + N ₂
D268.	NO	+ HNO		= HN + NO ₂
B283.	NO	+ HNO		= HO + N ₂ O
B284.	NO	+ HNO		= HO ₂ + N ₂
D248.	NO	+ HO		= H + NO ₂
D275.	NO	+ HO		= HN + O ₂
D286.	NO	+ HO		= HNO + O
B294.	NO	+ HO		= HO ₂ + N
D289.	NO	+ HO ₂		= HNO + O ₂
D295.	NO	+ HO ₂		= HO + NO ₂
D234.	NO	+ H ₂		= H + HNO
D260.	NO	+ H ₂		= HN + HO

REACTIONS OF NO

B299.	NO	+	H2		=	H2O	+	N	
D264.	NO	+	H2O		=	HN	+	HO2	
D280.	NO	+	H2O		=	HNO	+	HO	
D300.	NO	+	H2O		=	H2	+	NO2	
B305.	NO	+	N		=	N2	+	O	
B306.	NO	+	N	+	M	=	N2O	+	M
C307.	NO	+	NO		=	N	+	NO2	
A314.	NO	+	NO		=	N2	+	O2	
A315.	NO	+	NO		=	N2O	+	O	
A316.	NO	+	NO2		=	N2O	+	O2	
C310.	NO	+	N2		=	N	+	N2O	
A317.	NO	+	N2O		=	NO2	+	N2	
C312.	NO	+	O		=	N	+	O2	
A318.	NO	+	O	+	M	=	NO2	+	M
A319.	NO	+	O2		=	NO2	+	O	

REACTIONS OF NO₂

C313.	NO ₂	+ M	= N	+ O ₂	+ M
C318.	NO ₂	+ M	= NO	+ O	+ M
B 42.	NO ₂	+ CH	= CHN	+ O ₂	
B 43.	NO ₂	+ CH	= CHO	+ NO	
B 44.	NO ₂	+ CH	= CN	+ HO ₂	
B 45.	NO ₂	+ CH	= CO	+ HNO	
B 46.	NO ₂	+ CH	= CO ₂	+ HN	
B 84.	NO ₂	+ CHN	= CHO	+ N ₂ O	
B131.	NO ₂	+ CHO	= CO ₂	+ HNO	
D 73.	NO ₂	+ CH ₂	= CHN	+ HO ₂	
D110.	NO ₂	+ CH ₂	= CHO	+ HNO	
B161.	NO ₂	+ CH ₂	= CH ₂ O	+ NO	
D175.	NO ₂	+ CH ₃	= CH ₂ O	+ HNO	
B203.	NO ₂	+ CH ₃	= CH ₃ O	+ NO	
D209.	NO ₂	+ CH ₄	= CH ₃ O	+ HNO	
B217.	NO ₂	+ CN	= CO	+ N ₂ O	
B218.	NO ₂	+ CN	= CO ₂	+ N ₂	
B227.	NO ₂	+ CO	= CO ₂	+ NO	
B246.	NO ₂	+ H	= HN	+ O ₂	
B247.	NO ₂	+ H	= HNO	+ O	
B248.	NO ₂	+ H	= HO	+ NO	
B249.	NO ₂	+ H	= HO ₂	+ N	
B268.	NO ₂	+ HN	= HNO	+ NO	
B269.	NO ₂	+ HN	= HO	+ N ₂ O	
B270.	NO ₂	+ HN	= HO ₂	+ N ₂	

REACTIONS OF NO₂

B285.	NO ₂	+	HNO	=	HO ₂	+	N ₂ O
D288.	NO ₂	+	HO	=	HNO	+	O ₂
B295.	NO ₂	+	HO	=	HO ₂	+	NO
D263.	NO ₂	+	H ₂	=	HN	+	HO ₂
D279.	NO ₂	+	H ₂	=	HNC	+	HO
B300.	NO ₂	+	H ₂	=	H ₂ O	+	NO
D281.	NO ₂	+	H ₂ O	=	HNO	+	HO ₂
B307.	NO ₂	+	N	=	NO	+	NO
B308.	NO ₂	+	N	=	N ₂	+	O ₂
B309.	NO ₂	+	N	=	N ₂ O	+	O
B316.	NO ₂	+	NO	=	N ₂ O	+	O ₂
C317.	NO ₂	+	N ₂	=	NO	+	N ₂ O
C319.	NO ₂	+	O	=	NO	+	O ₂

REACTIONS OF N₂

C304.	N ₂	+ M	= N	+ N	+ M
B 47.	N ₂	+ CH	= CHN	+ N	
B 48.	N ₂	+ CH	= CN	+ HN	
D 50.	N ₂	+ CHO	= CH	+ N ₂ O	
D 82.	N ₂	+ CHO	= CHN	+ NO	
B132.	N ₂	+ CHO	= CN	+ HNO	
D 65.	N ₂	+ CH ₂	= CHN	+ HN	
D 67.	N ₂	+ CH ₂ O	= CHN	+ HNO	
D162.	N ₂	+ CH ₂ O	= CH ₂	+ N ₂ O	
D204.	N ₂	+ CH ₃ O	= CH ₃	+ N ₂ O	
D216.	N ₂	+ CO	= CN	+ NO	
D218.	N ₂	+ CO ₂	= CN	+ NO ₂	
D228.	N ₂	+ CO ₂	= CO	+ N ₂ O	
B250.	N ₂	+ H	= HN	+ N	
D271.	N ₂	+ HNO	= HN	+ N ₂ O	
D253.	N ₂	+ HO	= H	+ N ₂ O	
D267.	N ₂	+ HO	= HN	+ NO	
D282.	N ₂	+ HO	= HNO	+ N	
D270.	N ₂	+ HO ₂	= HN	+ NO ₂	
D284.	N ₂	+ HO ₂	= HNO	+ NO	
D296.	N ₂	+ HO ₂	= HO	+ N ₂ O	
D257.	N ₂	+ H ₂	= HN	+ HN	
D259.	N ₂	+ H ₂ O	= HN	+ HNO	
D301.	N ₂	+ H ₂ O	= H ₂	+ N ₂ O	
D310.	N ₂	+ NO	= N	+ N ₂ O	

REACTIONS OF N2

D317.	N2	+	NO2	=	NO	+	N2O		
C305.	N2	+	O	=	N	+	NO		
A320.	N2	+	O	+	M	=	N2O	+	M
C308.	N2	+	O2	=	N	+	NO2		
C314.	N2	+	O2	=	NO	+	NO		
A321.	N2	+	O2	=	N2O	+	O		

REACTIONS OF N2O

C306.	N2O	+ M	= N	+ NO	+ M
C320.	N2O	+ M	= N2	+ O	+ M
B 49.	N2O	+ CH	= CHN	+ NO	
B 50.	N2O	+ CH	= CHO	+ N2	
B 51.	N2O	+ CH	= CN	+ HNO	
D 84.	N2O	+ CHO	= CHN	+ NO2	
D 66.	N2O	+ CH2	= CHN	+ HNO	
B162.	N2O	+ CH2	= CH2O	+ N2	
B204.	N2O	+ CH3	= CH3O	+ N2	
D217.	N2O	+ CO	= CN	+ NO2	
B228.	N2O	+ CO	= CO2	+ N2	
B251.	N2O	+ H	= HN	+ NO	
B252.	N2O	+ H	= HNO	+ N	
B253.	N2O	+ H	= HO	+ N2	
B271.	N2O	+ HN	= HNO	+ N2	
D269.	N2O	+ HO	= HN	+ NO2	
D283.	N2O	+ HO	= HNO	+ NO	
B296.	N2O	+ HO	= HO2	+ N2	
D285.	N2O	+ HO2	= HNO	+ NO2	
D258.	N2O	+ H2	= HN	+ HNO	
B301.	N2O	+ H2	= H2O	+ N2	
D278.	N2O	+ H2O	= HNO	+ HNO	
B310.	N2O	+ N	= NO	+ N2	
B317.	N2O	+ NO	= NO2	+ N2	
C309.	N2O	+ O	= N	+ NO2	

REACTIONS OF N₂O

REACTIONS OF O

B 52.	O	+ CH	+ M	= CHO	+ M
B 53.	O	+ CH		= CO	+ H
D 38.	O	+ CHN		= CH	+ NO
B 85.	O	+ CHN		= CHO	+ N
B 86.	O	+ CHN		= CN	+ HO
B 87.	O	+ CHN		= CO	+ HN
D 54.	O	+ CHO		= CH	+ O2
B133.	O	+ CHO		= CO	+ HO
B134.	O	+ CHO		= CO2	+ H
D 21.	O	+ CH2		= CH	+ HO
D104.	O	+ CH2		= CHO	+ H
B163.	O	+ CH2	+ M	= CH2O	+ M
B164.	O	+ CH2		= CO	+ H2
D 26.	O	+ CH2O		= CH	+ HO2
D113.	O	+ CH2O		= CHO	+ HO
D165.	O	+ CH2O		= CH2	+ O2
B187.	O	+ CH2O		= CO	+ H2O
B188.	O	+ CH2O		= CO2	+ H2
D 34.	O	+ CH3		= CH	+ H2O
D120.	O	+ CH3		= CHO	+ H2
D147.	O	+ CH3		= CH2	+ HO
D171.	O	+ CH3		= CH2O	+ H
B205.	O	+ CH3	+ M	= CH3O	+ M
D125.	O	+ CH3O		= CHO	+ H2O
D151.	O	+ CH3O		= CH2	+ HO2

REACTIONS OF O

D178.	O	+ CH3O	= CH2O + HO	
D206.	O	+ CH3O	= CH3 + O2	
D157.	O	+ CH4	= CH2 + H2O	
D182.	O	+ CH4	= CH2O + H2	
D196.	O	+ CH4	= CH3 + HO	
D207.	O	+ CH4	= CH3O + H	
B219.	O	+ CN	= CO + N	
B229.	O	+ CO + M	= CO2	+ M
D230.	O	+ CO2	= CO + O2	
B254.	O	+ H + M	= HO	+ M
D243.	O	+ HN	= H + NO	
B272.	O	+ HN + M	= HNO	+ M
B273.	O	+ HN	= HO + N	
D247.	O	+ HNO	= H + NO2	
D274.	O	+ HNO	= HN + O2	
B286.	O	+ HNO	= HO + NO	
B287.	O	+ HNO	= HO2 + N	
D255.	O	+ HO	= H + O2	
B297.	O	+ HO + M	= HO2	+ M
D298.	O	+ HO2	= HO + O2	
D236.	O	+ H2	= H + HO	
B302.	O	+ H2 + M	= H2O	+ M
D240.	O	+ H2O	= H + HO2	
D291.	O	+ H2O	= HO + HO	
D303.	O	+ H2O	= H2 + O2	

REACTIONS OF O

B311.	O	+ N	+ M	= NO		+ M
D312.	O	+ NO		= N	+ O2	
B318.	O	+ NO	+ M	= NO2		+ M
D319.	O	+ NO2		= NO	+ O2	
D305.	O	+ N2		= N	+ NO	
B320.	O	+ N2	+ M	= N2O		+ M
D309.	O	+ N2O		= N	+ NO2	
D315.	O	+ N2O		= NO	+ NO	
D321.	O	+ N2O		= N2	+ O2	
A322.	O	+ O	+ M	= O2		+ M

REACTIONS OF O₂

C322.	O ₂	+ M	= O	+ O	+ M
B 54.	O ₂	+ CH	= CHO	+ O	
B 55.	O ₂	+ CH	= CO	+ HO	
B 56.	O ₂	+ CH	= CO ₂	+ H	
D 42.	O ₂	+ CHN	= CH	+ NO ₂	
B 88.	O ₂	+ CHN	= CHO	+ NO	
B 89.	O ₂	+ CHN	= CN	+ HO ₂	
B 90.	O ₂	+ CHN	= CO	+ HNO	
B 91.	O ₂	+ CHN	= CO ₂	+ HN	
B135.	O ₂	+ CHO	= CO	+ HO ₂	
B136.	O ₂	+ CHO	= CO ₂	+ HO	
D 25.	O ₂	+ CH ₂	= CH	+ HO ₂	
D112.	O ₂	+ CH ₂	= CHO	+ HO	
B165.	O ₂	+ CH ₂	= CH ₂ O	+ O	
B166.	O ₂	+ CH ₂	= CO	+ H ₂ O	
B167.	O ₂	+ CH ₂	= CO ₂	+ H ₂	
D116.	O ₂	+ CH ₂ O	= CHO	+ HO ₂	
B189.	O ₂	+ CH ₂ O	= CO ₂	+ H ₂ O	
D124.	O ₂	+ CH ₃	= CHO	+ H ₂ O	
D150.	O ₂	+ CH ₃	= CH ₂	+ HO ₂	
D177.	O ₂	+ CH ₃	= CH ₂ O	+ HO	
B206.	O ₂	+ CH ₃	= CH ₃ O	+ O	
D179.	O ₂	+ CH ₃ O	= CH ₂ O	+ HO ₂	
D185.	O ₂	+ CH ₄	= CH ₂ O	+ H ₂ O	
D198.	O ₂	+ CH ₄	= CH ₃	+ HO ₂	

REACTIONS OF O₂

D210.	O ₂	+ CH ₄	= CH ₃ O + HO
B220.	O ₂	+ CN	= CO + NO
B221.	O ₂	+ CN	= CO ₂ + N
B230.	O ₂	+ CO	= CO ₂ + O
B255.	O ₂	+ H	= HO + O
B256.	O ₂	+ H + M	= HO ₂ + M
D246.	O ₂	+ HN	= H + NO ₂
B274.	O ₂	+ HN	= HNO + O
B275.	O ₂	+ HN	= HO + NO
B276.	O ₂	+ HN	= HO ₂ + N
B288.	O ₂	+ HNO	= HO + NO ₂
B289.	O ₂	+ HNO	= HO ₂ + NO
B298.	O ₂	+ HO	= HO ₂ + O
D239.	O ₂	+ H ₂	= H + HO ₂
D290.	O ₂	+ H ₂	= HO + HO
B303.	O ₂	+ H ₂	= H ₂ O + O
D292.	O ₂	+ H ₂ O	= HO + HO ₂
B312.	O ₂	+ N	= NO + O
B313.	O ₂	+ N + M	= NO ₂ + M
B319.	O ₂	+ NO	= NO ₂ + O
D308.	O ₂	+ N ₂	= N + NO ₂
D314.	O ₂	+ N ₂	= NO + NO
B321.	O ₂	+ N ₂	= N ₂ O + O
D316.	O ₂	+ N ₂ O	= NO + NO ₂

APPENDIX C

KINETIC DATA ANALYSIS FOR JET-STIRRED COMBUSTOR

As an approach to testing kinetic models which couple nitric oxide formation to combustion reactions, the jet-stirred combustor was used to study NO_x formation under kinetically controlled combustion conditions. The experimental data were compared with kinetic calculations performed by General Applied Science Laboratories for a well-stirred reactor. The agreement between theory and experiment was quite good for the combustion of hydrogen/air and carbon monoxide/air for which detailed mechanisms were used. A quasi-global mechanism for the combustion of propane/air resulted in substantial underprediction of NO_x formation. The results described here were presented at the Fourteenth Combustion Symposium (C-1).

The kinetic mechanism used in this study is based on a building-block approach. The mechanism for hydrogen combustion is the basic element. Additional reactions are included for carbon monoxide combustion and a rate-limited global step for hydrocarbon reaction to carbon monoxide and hydrogen is included to handle hydrocarbon combustion. The overall mechanism for hydrocarbon combustion is based upon a "quasi-global" concept originally developed to represent the combustion characteristics of a variety of hydrocarbon fuels (C-2). The reactions for the oxidation of nitrogen are included in the model and are coupled to the combustion reactions through common intermediates.

The mechanism for hydrogen combustion, given in Table C-1A, consists of four exchange reactions and four dissociation/recombination reactions. The values of the rates for these reactions were taken, when available, from Reference (C-3).

Three reactions were added for carbon monoxide combustion (Table C-1B); the carbon monoxide exchange reactions with hydroxyl radical and molecular oxygen, and the dissociation/recombination reaction leading to carbon dioxide.

The global step for hydrocarbon consumption



is assigned a rate of

$$5.52 \times 10^8 T \exp(-12400/T) (\text{C}_n\text{H}_m)^{1/2} (\text{O}_2)(p)^{-0.825}$$

in accordance with Reference (C-2), as noted above.

The principal reactions for the formation of nitric oxide in this study were the Zeldovich exchange reactions



$$k_f = 1.36 \times 10^{14} \exp(-37700/T)$$

TABLE C-1

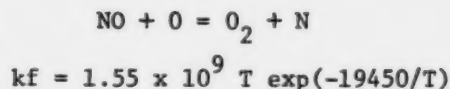
RATE PARAMETERS FOR KINETIC MODEL

$$k_f = AT^b \exp(-E/RT)$$

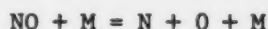
REACTION	A	b	E/R	Ref
A. Hydrogen Combustion				
$\text{OH} + \text{H}_2 = \text{H}_2\text{O} + \text{H}$	2.19×10^{13}	0	2590	C-3
$\text{OH} = \text{OH} = \text{O} + \text{H}_2\text{O}$	5.75×10^{12}	0	393	C-3
$\text{O} + \text{H}_2 = \text{H} + \text{OH}$	1.74×10^{13}	0	4750	C-3
$\text{H} + \text{O}_2 = \text{O} + \text{OH}$	2.24×10^{14}	0	8450	C-3
$\text{O} + \text{H} + \text{M} = \text{O}_2 + \text{M}$	1×10^{16}	0	0	C-4
$\text{O} + \text{O} + \text{M} = \text{O}_2 + \text{M}$	9.38×10^{14}	0	0	C-5
$\text{H} + \text{H} + \text{M} = \text{H}_2 + \text{M}$	5×10^{15}	0	0	C-4
$\text{H} + \text{OH} + \text{M} = \text{H}_2\text{O} + \text{M}$	1×10^{17}	0	0	C-3
B. Carbon Monoxide Combustion (additional reactions)				
$\text{CO} + \text{OH} = \text{H} + \text{CO}_2$	5.6×10^{11}	0	543	C-3
$\text{CO} + \text{O}_2 = \text{CO}_2 + \text{O}$	3×10^{12}	0	25000	C-6
$\text{CO} + \text{O} + \text{M} = \text{CO}_2 + \text{M}$	1.8×10^{19}	-1	2000	C-7

Reverse reaction rate, k_r , is obtained from k_f and the equilibrium constant, K_c .

and



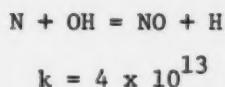
The values for the rate constants were taken from Reference (C-3). Other reactions involving nitric oxide such as



and



as well as NO oxidation reactions of interest in atmospheric studies are available in the model (C-2) for completeness but are not important under the conditions of this study. The reaction (C-8)



was not included in the basic calculations; however, under fuel rich conditions where H and OH concentrations became substantial, additional calculations including this reaction were made to test its importance.

The most crucial experimental measurements for this study were the mixture ratios, the reaction temperatures and the concentrations of NO_x . The mixture ratios could be determined to $\pm 2\%$ with calibrated rotameters. The reaction temperatures could be determined to $\pm 10^\circ\text{K}$ with consideration given to radiant heat losses and reproducibility. The nitrogen oxide measurements could be made to ± 2 ppm with either the Enviometrics or Du Pont analyzers (a Thermo Electron chemiluminescent analyzer now in use in our laboratory can give results better than ± 1 ppm). Cross-checks have been run with these instruments in selected experiments.

The temperatures for the calculations were determined in the following manner. The measured temperatures were compared to the calculated heat losses in a well-stirred reactor at the measured temperature. The heat loss was converted to an overall heat transfer coefficient

$$H = mC(T_o - T_m)/(T_m - T_a)$$

where C is dQ/dT , T_o is the temperature of a well-stirred reactor operating without heat losses, T_m is the measured temperature, and T_a is the ambient temperature. The heat transfer coefficients so determined were averaged and the average value was used to calculate a smoothed temperature curve through the data. These temperatures were given by

$$T = (\bar{H}T_a + \dot{m}CT_o)/(\bar{H} + \dot{m}C)$$

The calculated temperature was found to be relatively insensitive to the actual value of the heat transfer coefficient with a 10% difference in $\bar{h}$ corresponding to about a 10°K difference in temperature. Because of this insensitivity to $\bar{h}$, it was decided to assume a constant $\bar{h}$ for all cases. This method of temperature determination allows the calculations to be performed at pre-selected mixture ratios while utilizing all the temperature measurements for a given combustion system. Furthermore, in cases where the combustion temperature exceeded the limits of measurement for a Pt/Pt 10% Rh thermocouple (2040°K), the heat transfer coefficient was used to determine the experimental temperature. The measured (open symbols) and calculated (solid symbols) values of the combustion temperatures for hydrogen carbon monoxide and propane, respectively, with air are shown in Figure C-1.

The measurements of NO_x for the three fuel/air combinations were taken at mixture ratios ranging between about 50% and 160% stoichiometric air. Temperatures were measured, where possible, simultaneously with species measurements. The NO_x measurements are believed to be within the 2 ppm error limits previously stated, with the exception of the hydrogen data between 75% and 105% stoichiometric air, where the temperatures were above those allowable for continuous operation of the combustor. The uncertainty within this range of mixture ratios for hydrogen/air is assigned at $\pm 20\%$ because of the shortened duration of testing at a given setting. The results for the three fuel/air combinations are presented in Table C-2.

The NO_x results for hydrogen/air are shown in Figure C-2. The experimental results are reported on an "as measured" basis with water removed to a 1% concentration. The calculated results plotted in the same Figure were also corrected for water removal. The agreement between the measured values and calculated values is good, with the calculated values slightly higher than the experimental on the fuel-lean side and slightly below the experimental on the fuel-rich side.

The results for carbon monoxide/air are shown in Figure C-3. To aid combustion, hydrogen was added to the combustion zone at a constant rate amounting to about 1% (volume) of the carbon monoxide rate at 150% stoichiometric air and about 0.5% at 85% stoichiometric air. Although the carbon monoxide was "moist", the correction for water is negligible. The agreement between the experimental and calculated values of NO_x is quite remarkable considering the state of knowledge of the combustion reactions and the temperature sensitivity of the NO_x formation rates.

The agreement between the experimental values and the calculations is less satisfactory for propane/air (Figure C-4). The calculations under-predict the measurements by about a factor of four on the lean side and about an order of magnitude on the rich side. As will be discussed later, since the mechanism used for propane combustion depends on the mechanisms of hydrogen and carbon monoxide combustion, it is significant that these values are low.

FIGURE C-1

REACTOR TEMPERATURES

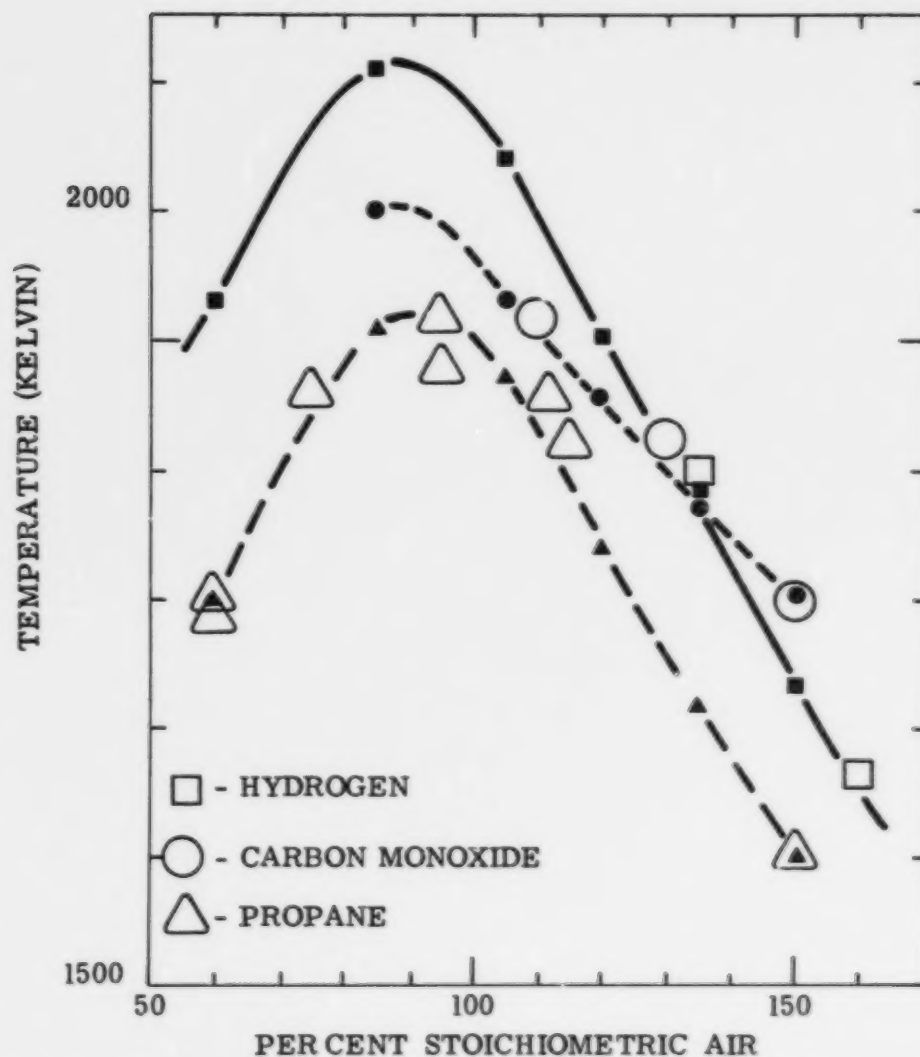


FIGURE C-1 - REACTOR TEMPERATURES FOR HYDROGEN/AIR, CARBON MONOXIDE/AIR AND PROPANE/AIR IN THE JET-STIRRED COMBUSTOR. OPEN SYMBOLS INDICATE EXPERIMENTAL TEMPERATURES. SOLID SYMBOLS INDICATE TEMPERATURES AT WHICH CALCULATIONS WERE MADE.

TABLE C-2

COMPARISON OF EXPERIMENTAL AND THEORETICAL RESULTS
FOR THE JET-STIRRED COMBUSTOR

Per Cent Stoichiometric Air	Temperature (calc from $\bar{H}$) (k)	NO _x measured (ppm)	NO _x calculated (ppm)
Reaction Volume = 14.5 cm			
Fuel: Hydrogen Air rate: 0.70 l/sec $T_I = 300^\circ\text{K}$			
60	2030	--	1.5
65	2080	13	
65	2080	15	
70	2120	20	
70	2120	20	
75	2165	25	
77	2180	35	
85	2210	--	34
90	2210	60	
99	2175	45	
105	2140	--	70
111	2090	40	
120	2000	--	40
135	1880	--	16
140	1830	7	
150	1730	--	3
162	1640	0	
190		0	
Fuel: Carbon Monoxide Air Rate 0.61 l/sec $T_I = 450^\circ\text{K}$			
76		80	
76		110	
85	2100	--	140
87	2100	118	
87	2100	120	
98	2080	97	
105	2030	--	105
118	1965	80	
120	1960	--	70
135	1870	--	30
146	1820	20	
150	1805	--	16

TABLE C-2 (Cont'd)

Per Cent Stoichiometric Air	Temperature (calc from $\bar{H}$) (k)	NO _x measured (ppm)	NO _x calculated (ppm)
Reaction Volume = 14.5 cm ³			
Fuel: Propane Air Rate = 0.61 l/sec T _I = 300°K			
52		7	
60	1800	49	
60	1800	50	1
60	1800	55	
71	1900	100	
71	1900	102	
78	1965	118	
78	1965	119	
85	2010	--	13
87	2015	120	
87	2015	120	
87	2015	110	
99	2005	105	
99	2005	90	
105	1970	--	30
111	1925	70	
111	1925	60	
111	1925	50	
120	1840	--	11
131	1750	40	
131	1750	29	
135	1715	--	3
150	1600	--	1
155	1570	8	
155	1570	6	

FIGURE C-2

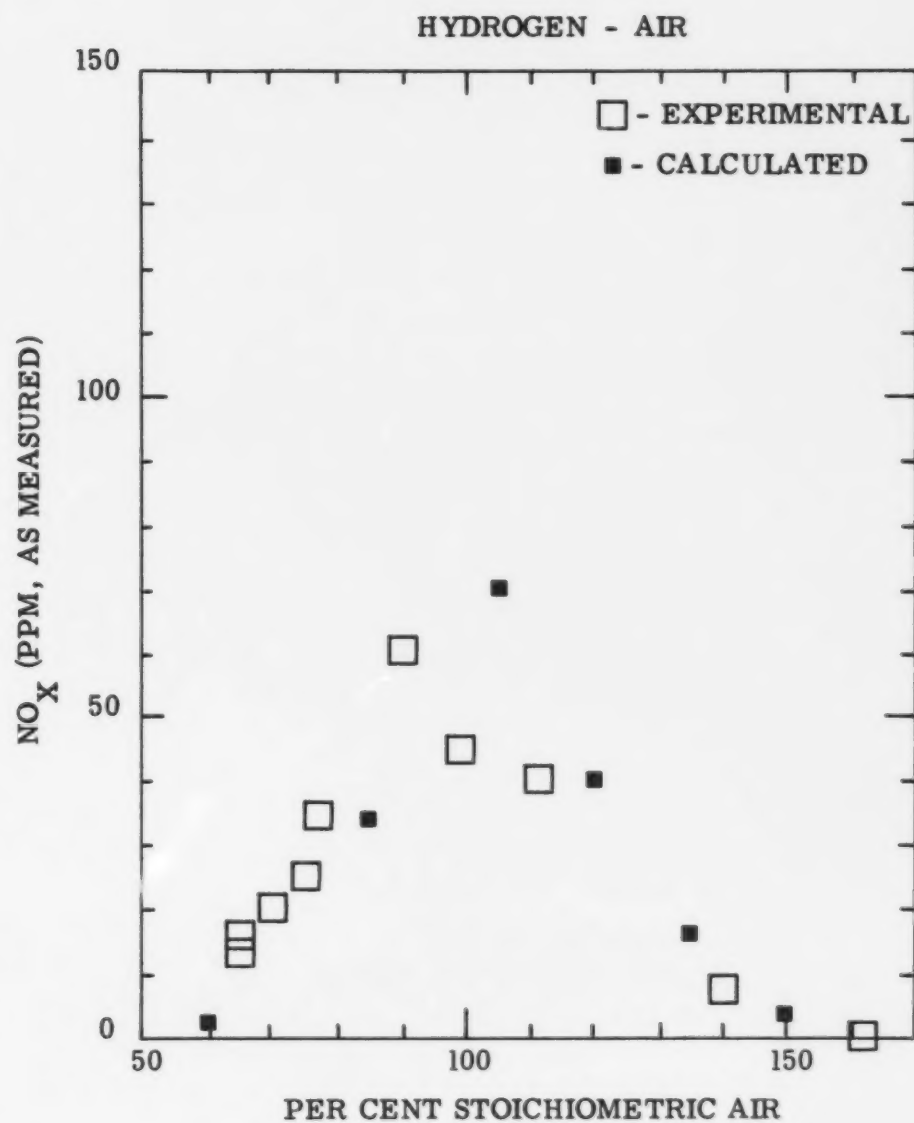


FIGURE C-2 - COMPARISON OF EXPERIMENTAL AND THEORETICAL CONCENTRATIONS OF NO_x IN THE JET-STIRRED COMBUSTOR FOR HYDROGEN/AIR. ^x

FIGURE C-3

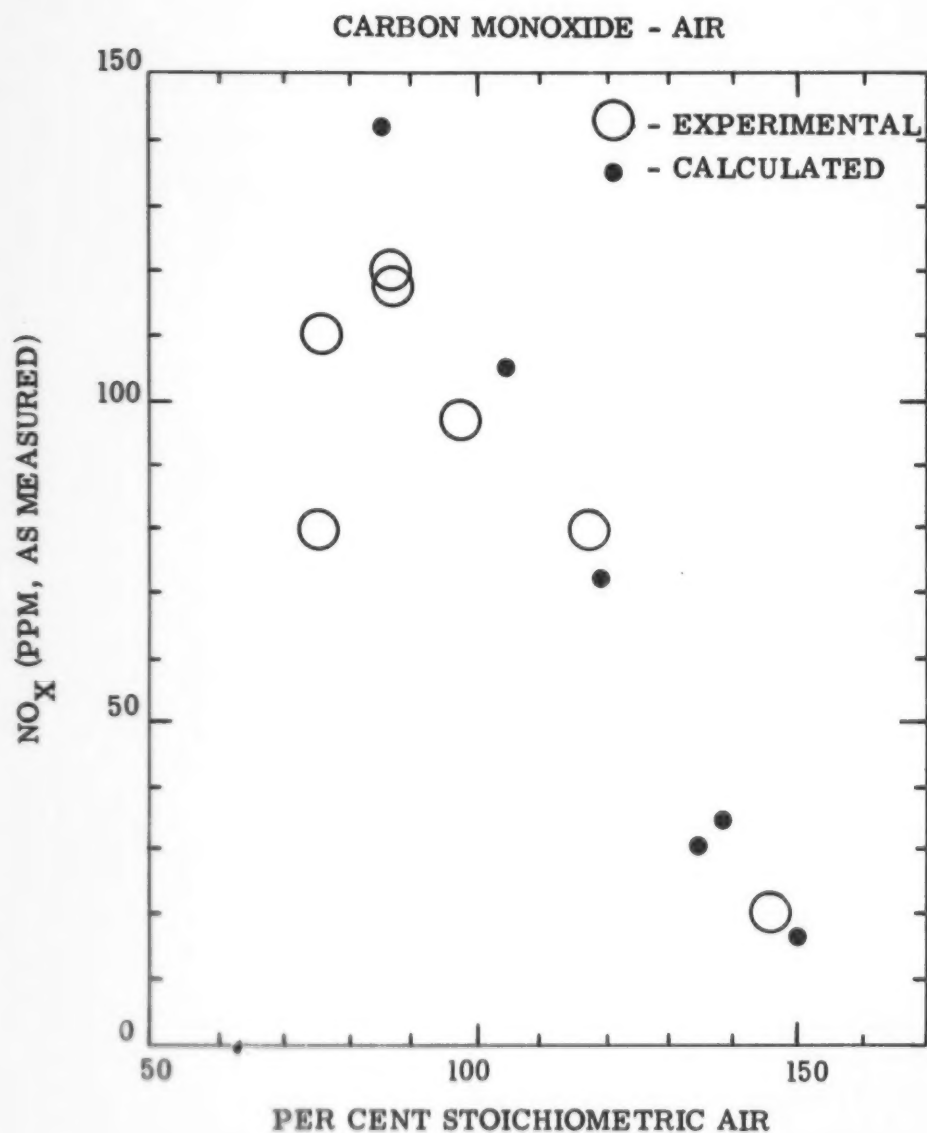


FIGURE C-3 - COMPARISON OF EXPERIMENTAL AND THEORETICAL CONCENTRATIONS OF NO_x IN THE JET-STIRRED COMBUSTOR FOR CARBON MONOXIDE/AIR.

FIGURE C-4

PROPANE - AIR

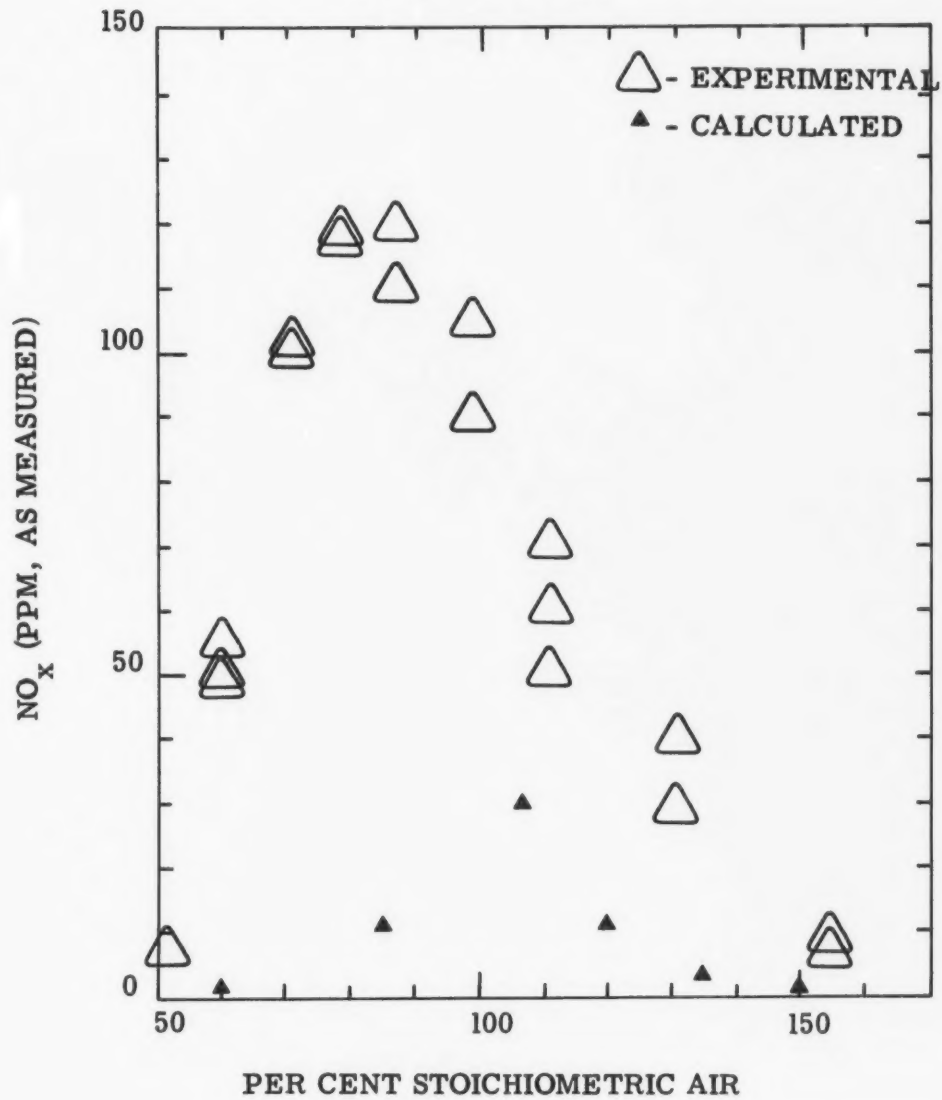


FIGURE C-4 -COMPARISON OF EXPERIMENTAL AND THEORETICAL CONCENTRATIONS OF NO_x IN THE JET-STIRRED COMBUSTOR FOR PROPANE/AIR.

The results of the calculations for hydrogen and carbon monoxide combustion with air indicate that nitric oxide formation can be predicted with good accuracy, even in a flame zone, provided the concentrations of combustion intermediates can be calculated. The NO_x values are under-predicted using a quasi-global treatment for propane. It should be stressed that the values for the rate constants used in this study were pre-selected and were not adjusted to give best fit to the data. The purpose of this study was not to determine rate constants but to test the capabilities of kinetic modeling and validate the use of the jet-stirred combustor for testing kinetic models.

In the mechanisms used for this study, the reactions of primary importance for nitric oxide formation are the exchange reactions of the Zeldovich mechanism. However, the concentration of the oxygen atoms is not assumed to be in equilibrium with molecular oxygen; it is determined by the detailed kinetic mechanism. In fact, in the intensely backmixed system with chain branching reactions occurring throughout the combustion zone, the oxygen atom concentration can be substantially above that in equilibrium with the molecular oxygen concentration.

"Superequilibrium" oxygen atom concentrations have been a matter of discussion in the recent literature. In the case of this study, that term is not unambiguous. There are two "types" of equilibrium concentrations for oxygen atoms that can be considered. One is a "total" equilibrium concentration calculated by minimization of free energy of the total system; the other is a "partial" equilibrium concentration determined by combining the measured or calculated molecular oxygen concentration with the equilibrium constant for oxygen dissociation. In a well-stirred reactor, fresh reactants are continuously mixed with products in the combustion zone. Thus the concentration of molecular oxygen is above the value for total equilibrium, especially under fuel-rich conditions where the concentration of molecular oxygen can exceed the total equilibrium concentration by orders of magnitude. For the purpose of this discussion the partial equilibrium oxygen atom concentration will be used as the reference point.

Thus, under fuel-lean conditions, the well-stirred reactor calculations indicate that oxygen atom concentrations exceed the partial equilibrium value by up to a factor of 12 for hydrogen and up to a factor of 100 for propane. Under fuel-rich conditions (60% stoichiometric air) the oxygen atom concentrations exceed those calculated from $K(\text{O}_2)^{1/2}$ by a factor of 1.2 for hydrogen and about a factor of 50 for propane. The calculated concentrations of molecular and atomic oxygen are shown in Figure C-5.

The discussion of "superequilibrium" oxygen concentrations has an interesting extension under fuel-rich conditions for propane-air combustion in the jet-stirred combustor. The concentrations of nitric oxide observed experimentally at 60% stoichiometric air are more than an order of magnitude above those that would be calculated if the system were in "total"

FIGURE C-5

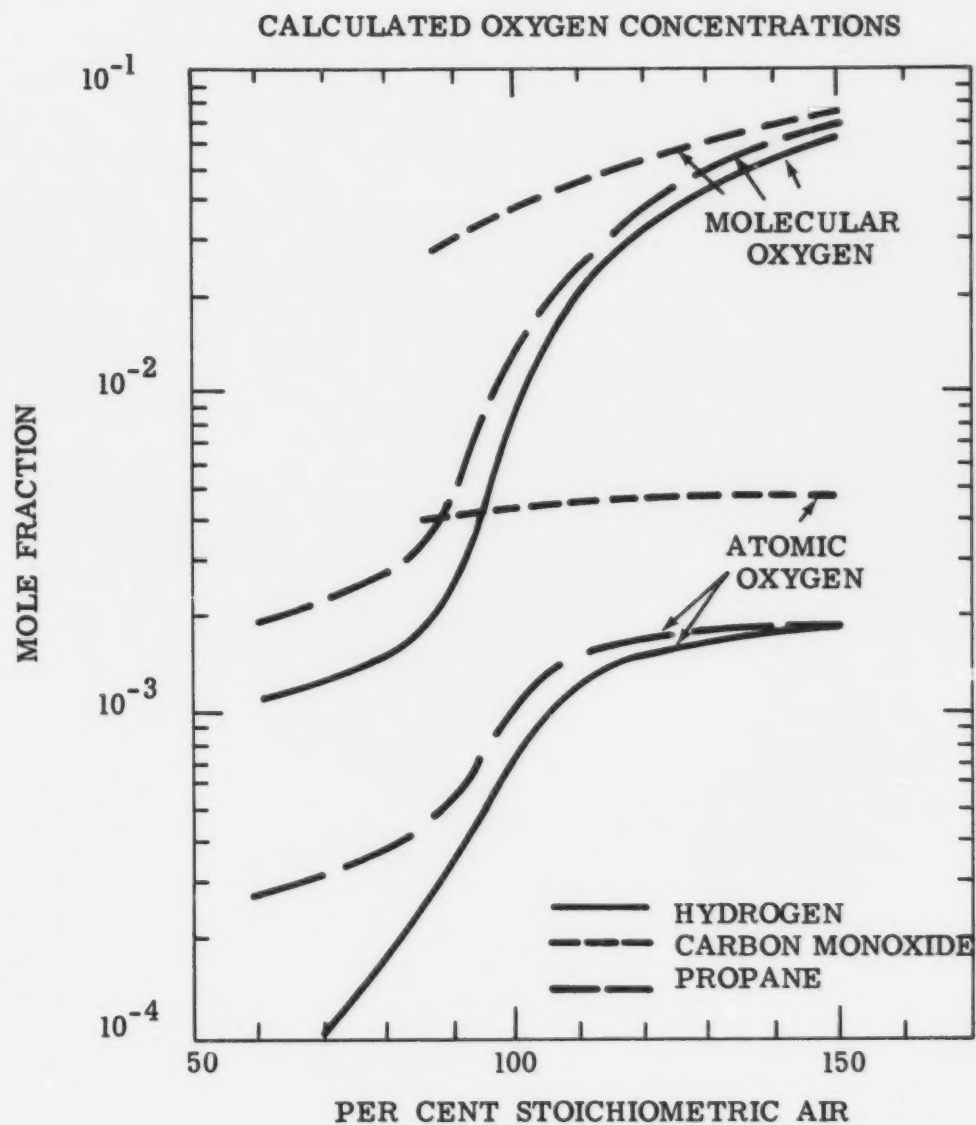


FIGURE C-5 - CALCULATED CONCENTRATIONS OF MOLECULAR AND ATOMIC OXYGEN IN THE JET-STIRRED COMBUSTOR FOR HYDROGEN, CARBON MONOXIDE AND PROPANE COMBUSTION.

equilibrium at the specified temperature. However, since both molecular and atomic oxygen are also above their "total" equilibrium concentrations by five and four orders of magnitude respectively under fuel rich conditions, there is still a driving force to produce more nitric oxide. The model does predict an NO level above that for "total" equilibrium at 60% stoichiometric air for propane but still under-predicts the observed level by about an order of magnitude. Thus, if a plug flow reactor were placed in series with the jet-stirred combustor and sufficient residence time at combustion temperature were allowed for the combustion gases to approach equilibrium, the concentration of nitric oxide would decrease to approach equilibrium.

In the case of hydrogen and carbon monoxide combustion, the exchange reactions of the Zeldovich mechanism (coupled to the combustion reactions which determine the oxygen atom concentrations) appear to be adequate for the prediction of nitric oxide formation. Under fuel rich conditions for hydrogen, the measured values are somewhat higher than the predictions suggesting that additional reactions may be required in the model. In fact, when the reaction



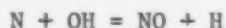
was included for hydrogen combustion under rich conditions, the formation of NO increased by up to 20%. The inclusion of this reaction in the propane mechanism had about the same percentage effect under fuel-rich conditions.

As discussed earlier, a quasi-global mechanism was used for propane combustion. In this quasi-global mechanism, the hydrocarbon is oxidized in a rate-limited single step to carbon monoxide and hydrogen, and the combustion of these intermediates is then described by the same mechanism as was used for carbon monoxide and hydrogen combustion. While substantial oxygen atom concentrations are predicted by the model, the predictions for nitric oxide formation fall below the measured values by about a factor of four under lean conditions and about a factor of ten under rich conditions.

Alternatives to the quasi-global approach to propane combustion coupled to the Zeldovich exchange reactions are possible. A more complete mechanism for propane combustion might lead to better agreement between calculations and experiments. Intermediates in the combustion mechanism might alter the balance of atomic oxygen and atomic nitrogen and such intermediates certainly exist throughout the reaction zone of the jet-stirred combustor. However, under fuel-rich conditions for propane, it does not appear likely that changes in oxygen atom concentration would be sufficient to account for an order of magnitude in NO_x production. Thus, the influence of additional reactions directly involved in the formation of NO or perhaps in the formation of readily oxidizable nitrogenous intermediates cannot be dismissed at this time. One must, however, exercise great caution to avoid adjusting parameters to fit existing data. Reactions which have little

significance in the overall combustion scheme may be of importance in NO formation under specific conditions. The valuation of the reactions significant for the characterization of gross combustion phenomena is a formidable task by itself. The numerous additional reactions which may be significant under specific conditions for the formation of parts per million of nitric oxide presents even more difficult problems. The jet-stirred reactor data will provide a comparison point for parametric studies of the reaction rates included in the kinetics evaluation described elsewhere in this report.

The comparison of NO_x concentrations between experiment and calculation for the case of hydrogen/air combustion in the jet-stirred combustor indicates that the mechanism of coupled combustion and NO_x formation is fairly well determined. Under fuel-rich conditions the inclusion of the reaction



in addition to the Zeldovich exchange reactions improves the agreement between theory and experiment.

Good agreement is also found in the case of carbon monoxide/air combustion. In both the hydrogen and carbon monoxide cases, substantial oxygen atom concentrations are calculated and accounting for their presence is apparently sufficient to allow prediction of nitric oxide formation.

For propane/air combustion, although substantial oxygen atom concentrations are also predicted, the use of a quasi-global mechanism for hydrocarbon combustion results in underprediction of nitric oxide by about a factor of four under fuel-lean conditions and about an order of magnitude under fuel-rich conditions. It is not clear at present whether a more detailed combustion mechanism would resolve the differences or whether additional reactions for the formation of nitric oxide are required. However, it does not seem likely that an order of magnitude difference under fuel rich conditions could be resolved by changes in oxygen atom concentration alone. It is clear that a quasi-global approach, which has been found to be useful for the representation of combustion characteristics of a variety of hydrocarbon fuels, is not adequate for the prediction of nitric oxide formation.

In the jet-stirred combustor under fuel-rich conditions with propane, the nitric oxide concentrations can be above those calculated for total equilibrium at the specified mixture ratio. This NO "overshoot" can be understood in terms of the model, in part by the "superequilibrium" concentrations of molecular and atomic oxygen in a well-stirred reactor under fuel-rich conditions. These "superequilibrium" molecular oxygen concentrations are caused by the continuous mixing of fresh reactants with products in the reaction zone.

The jet-stirred combustor, operated in a manner that approaches a well-stirred reactor, provides highly non-equilibrium behavior in a well-defined system and, therefore, provides a severe test for any kinetic model. As kinetic mechanisms become more complex, critical evaluation of the component reactions becomes increasingly important. The coupling of kinetic modeling with sophisticated fluid mechanic and heat transfer modeling is ultimately required for application to pollutant formation in practical combustion systems.

REFERENCES

- C-1 Engleman, V. S., Bartok, W., Longwell, J. P., and Edelman, R. B., Fourteenth Symposium (International) on Combustion, p. 755, The Combustion Institute (1973).
- C-2 Edelman, R. and Fortune, O., "A Quasi-Global Chemical Kinetic Model for the Finite Rate Combustion of Hydrocarbon Fuels," AIAA Paper 69-86, Seventh Aerospace Sciences Meeting, 1969.
- C-3 Baulch, D. L., et al., "Critical Evaluation of Rate Data for Homogeneous, Gas-Phase Reactions of Interest in High-Temperature Systems," Nos. 1-5, Department of Physical Chemistry, The University, Leeds, England.
- C-4 Moretti, G., AIAA J. 3, 223 (1965).
- C-5 Amman, P. R. and Timmins, R. S., AIChE J. 12, 956 (1966).
- C-6 Brokaw, R. S., Eleventh Symposium (International) on Combustion, p. 1063, The Combustion Institute, 1967.
- C-7 Carnicom, M. L., "Reaction Rates for High Temperature Air with Carbon and Sodium Impurities," Sandia Laboratories, SC-R-68-1797, May 1968.
- C-8 Campbell, I. M. and Thrush, B. A., Trans. Faraday Soc. 64, 1265 (1968).

D-1

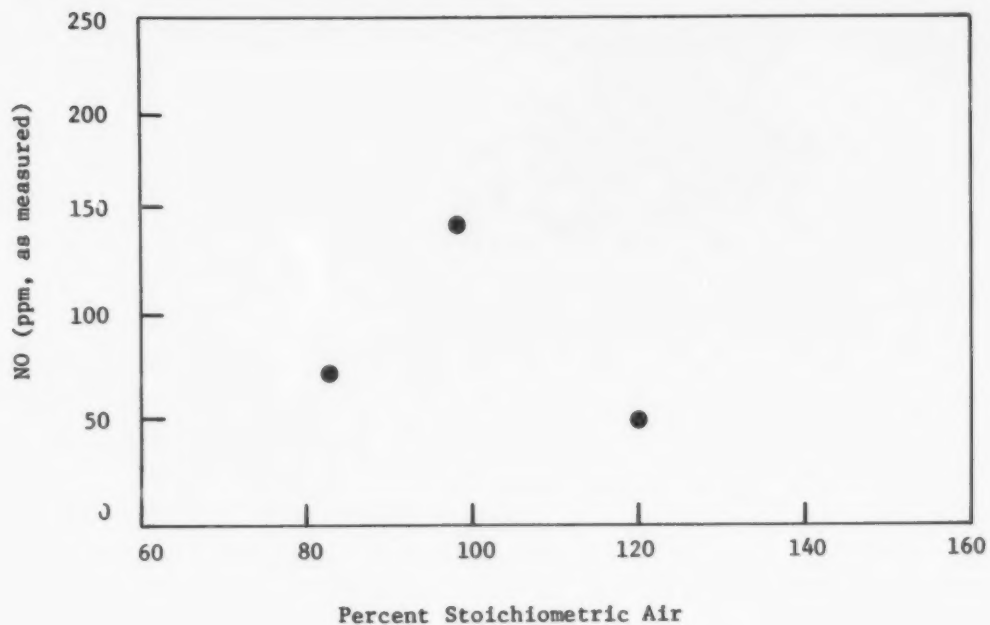
APPENDIX D

NO/NO_x PLOTS

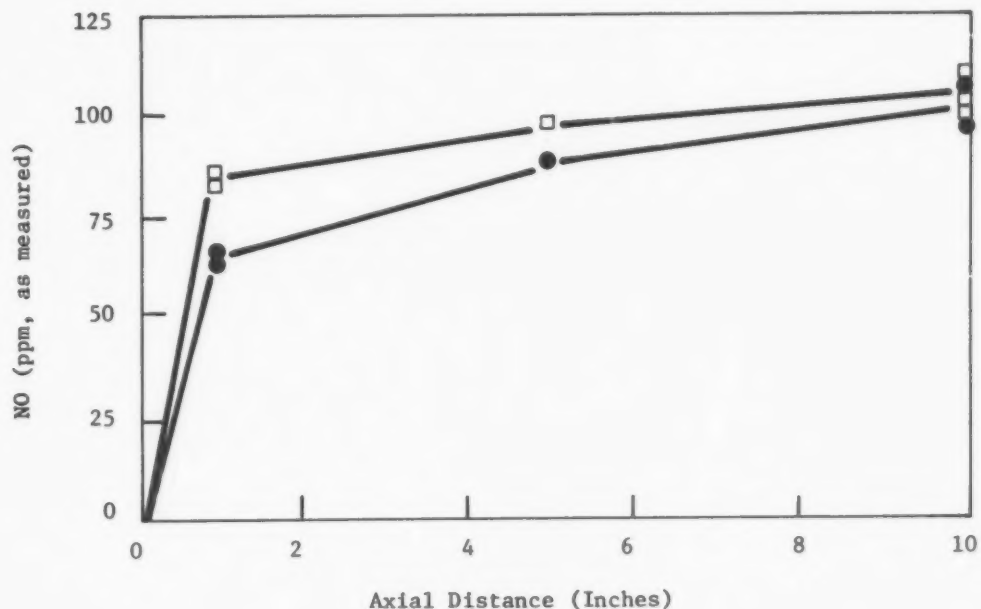
● - NO

■ - NO_x

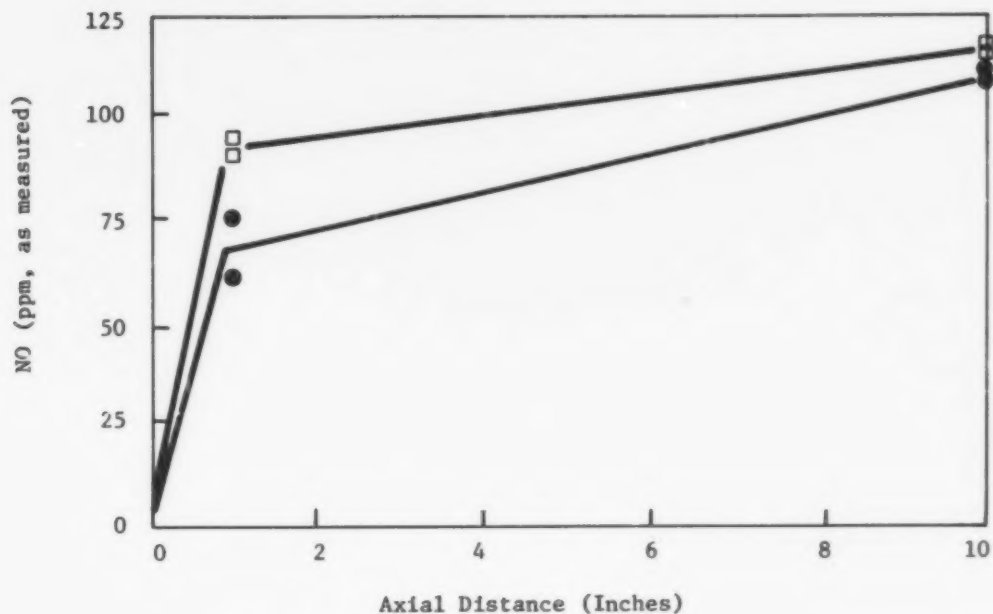
Run Number 101, Premixed Flat Flame Burner (Laminar), Propane Fuel,
Stoichiometric Air, Cold Wall



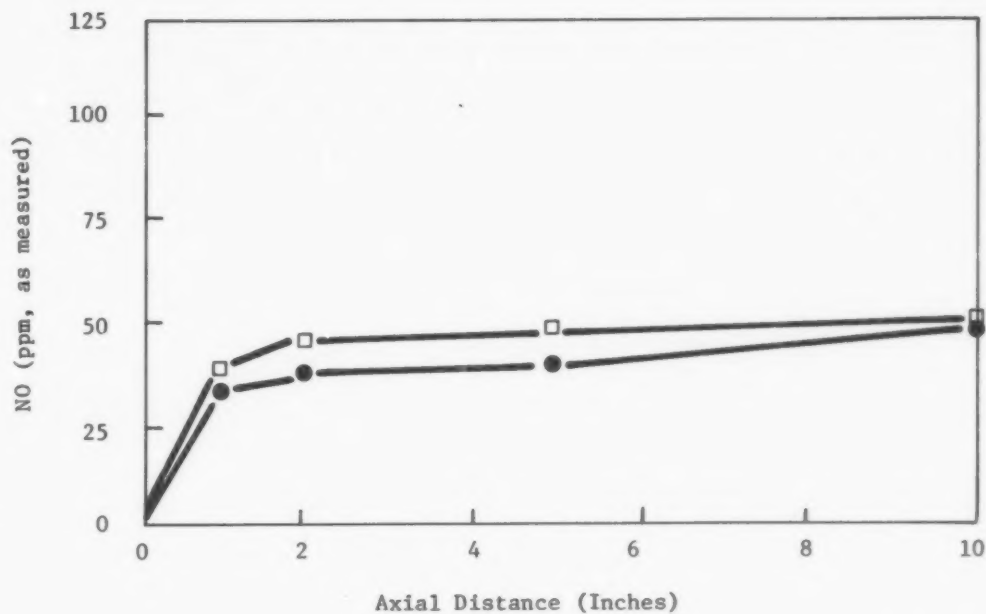
Run Number 102, Premixed Flat Flame Burner (Laminar), Propane Fuel,
106% Stoichiometric Air, Cold Wall



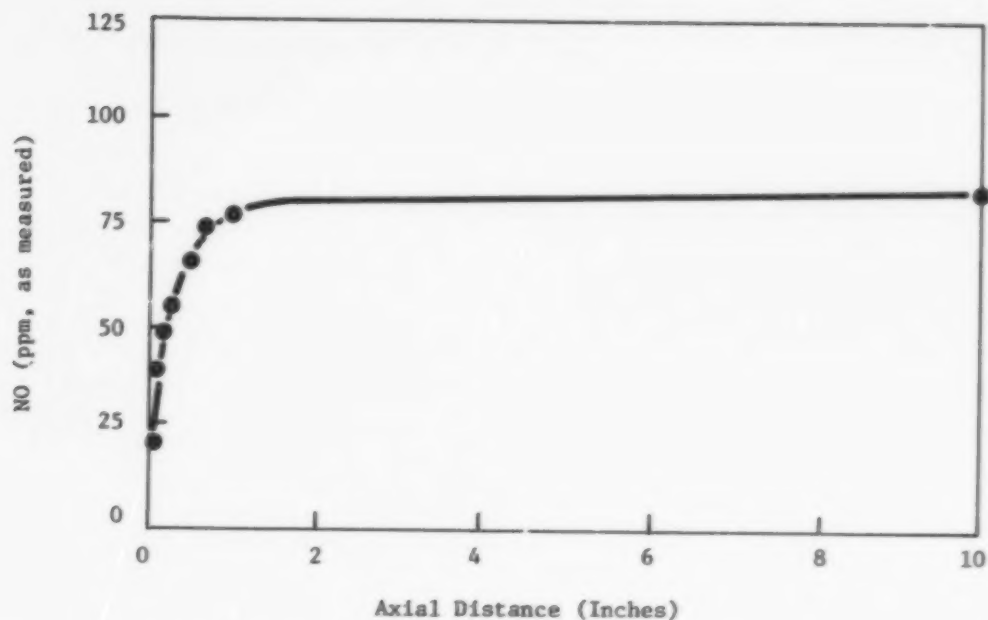
Run Number 103, Premixed Flat Flame Burner (Laminar), Propane Fuel,
103% Stoichiometric Air, Cold Wall



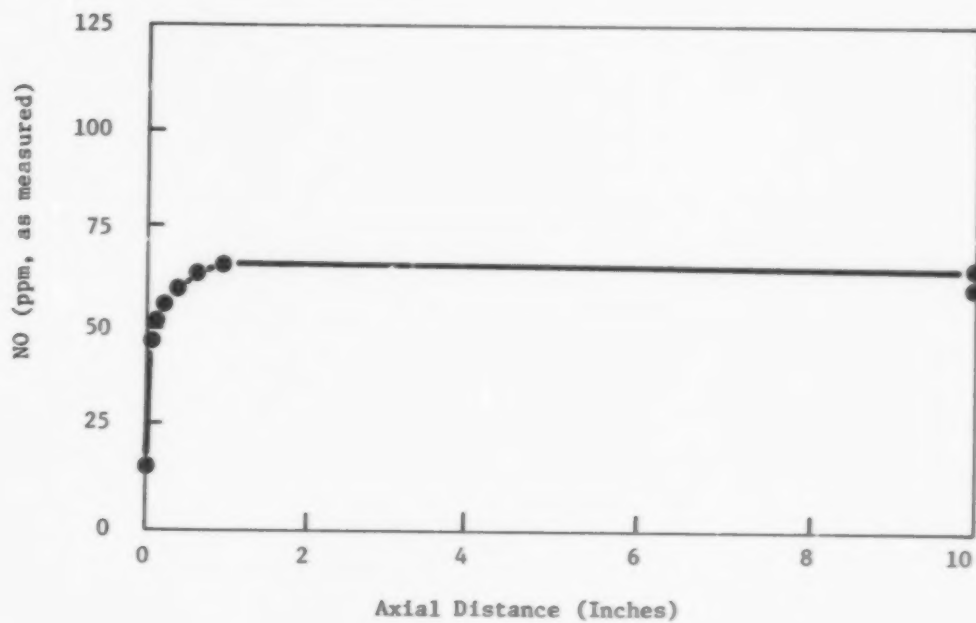
Run Number 103, Premixed Flat Flame Burner (Laminar), Propane Fuel,
122% Stoichiometric Air, Cold Wall



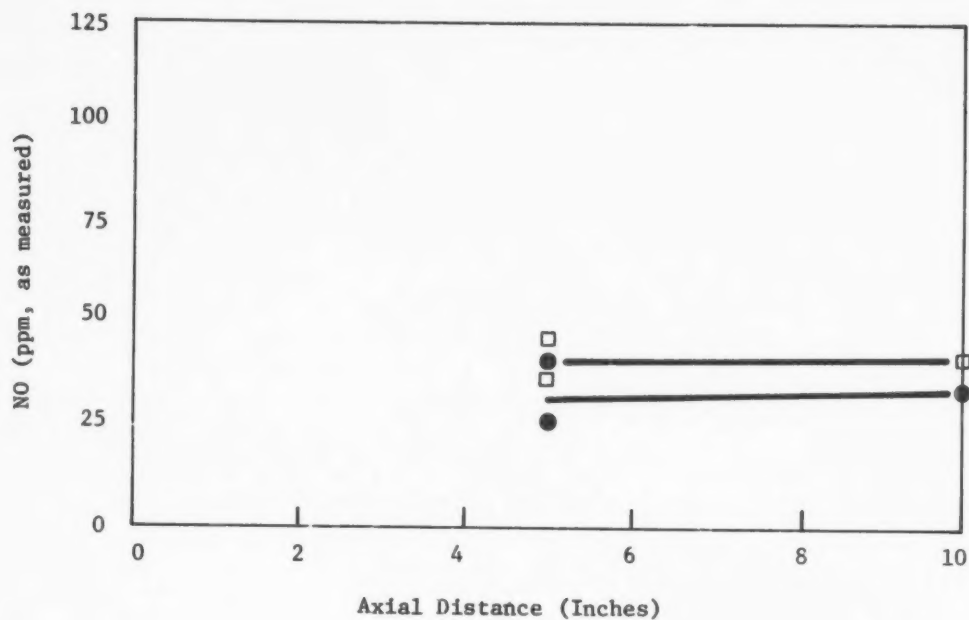
Run Number 104, Premixed Flat Flame Burner (Laminar), Propane Fuel,
94% Stoichiometric Air, Cold Wall



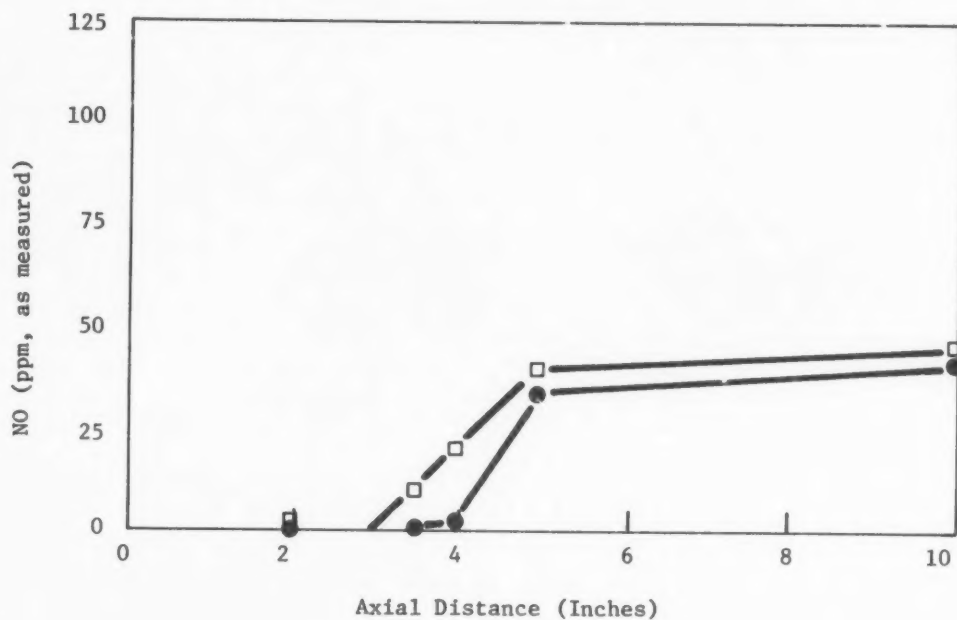
Run Number 104, Premixed Flat Flame Burner (Laminar), Propane Fuel,
83% Stoichiometric Air, Cold Wall



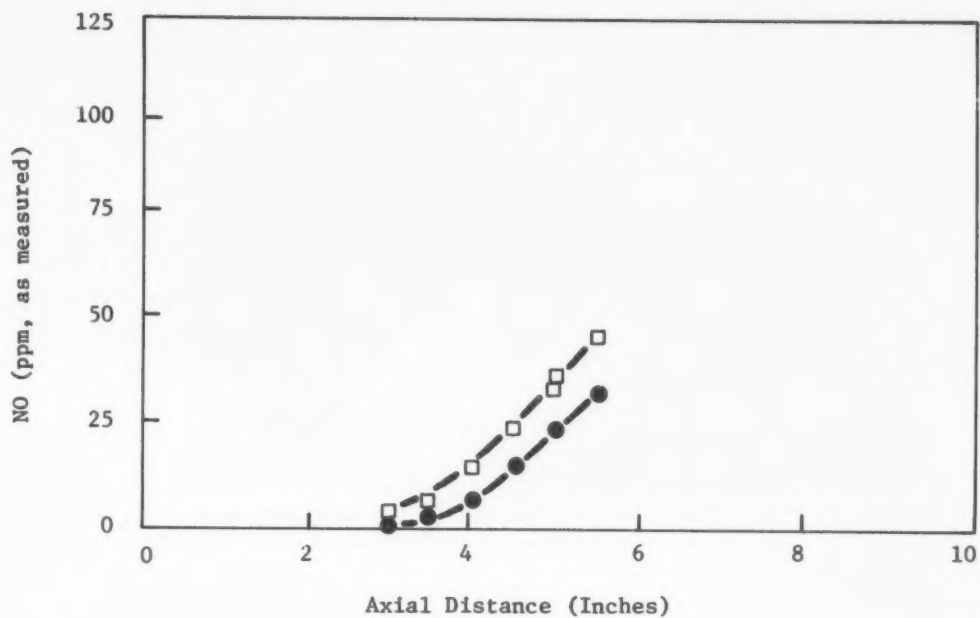
Run Number 105, Stabilized Diffusion Flame Burner (Turbulent),
Methane Fuel, 101% Stoichiometric Air, Cold Wall



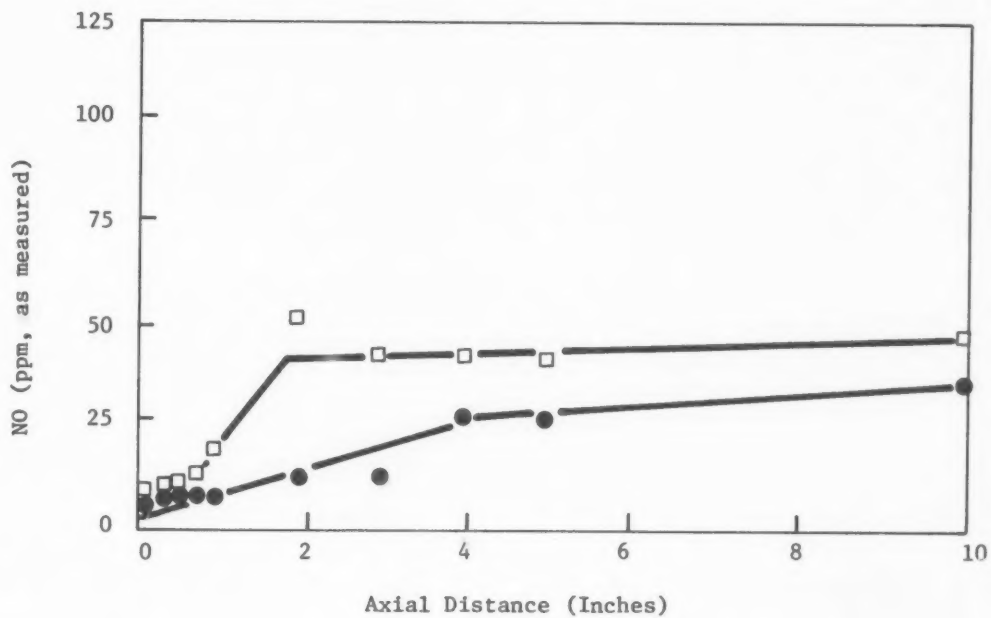
Run Number 106, Stabilized Diffusion Flame Burner (Turbulent),
Methane Fuel, 101% Stoichiometric Air, Cold Wall



Run Number 108, Stabilized Diffusion Flame Burner (Turbulent),
Methane Fuel, 120% Stoichiometric Air, Cold Wall

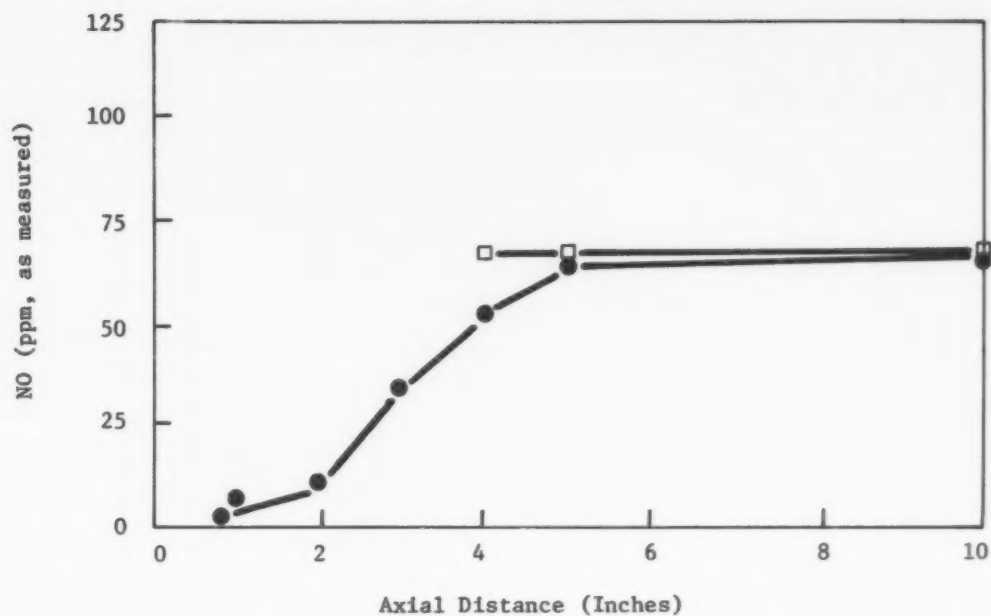


Run Number 109, Stabilized Diffusion Flame Burner (Laminar), Methane
Fuel, 107% Stoichiometric Air, Cold Wall

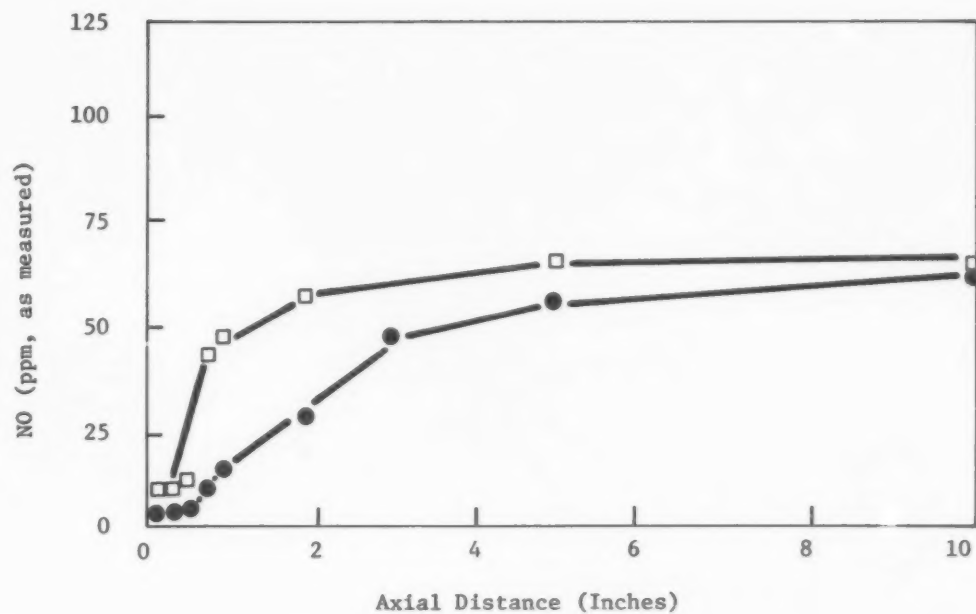


D-6

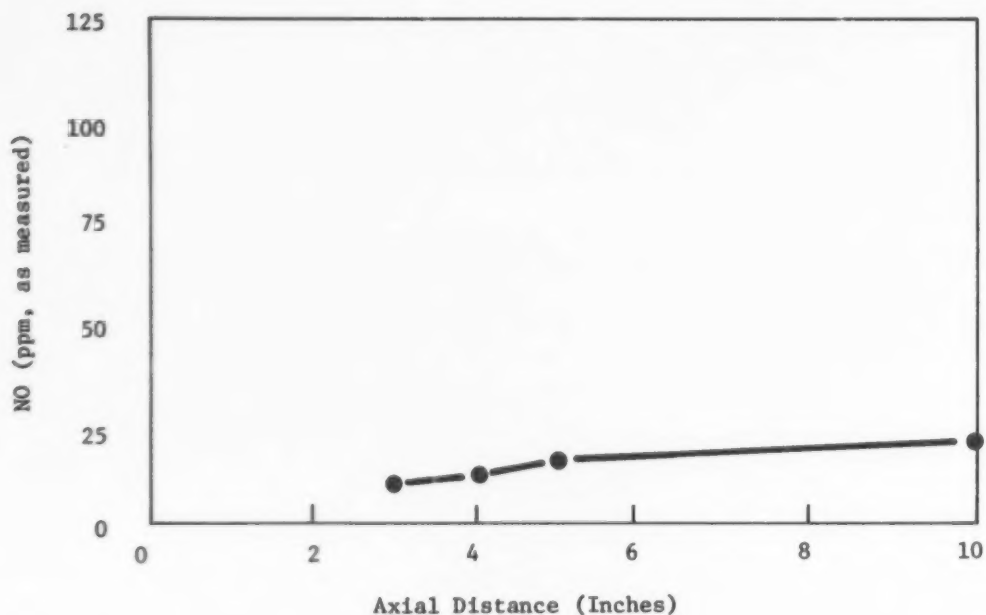
Run Number 109, Stabilized Diffusion Flame Burner (Laminar), Methane Fuel, 128% Stoichiometric Air, Cold Wall



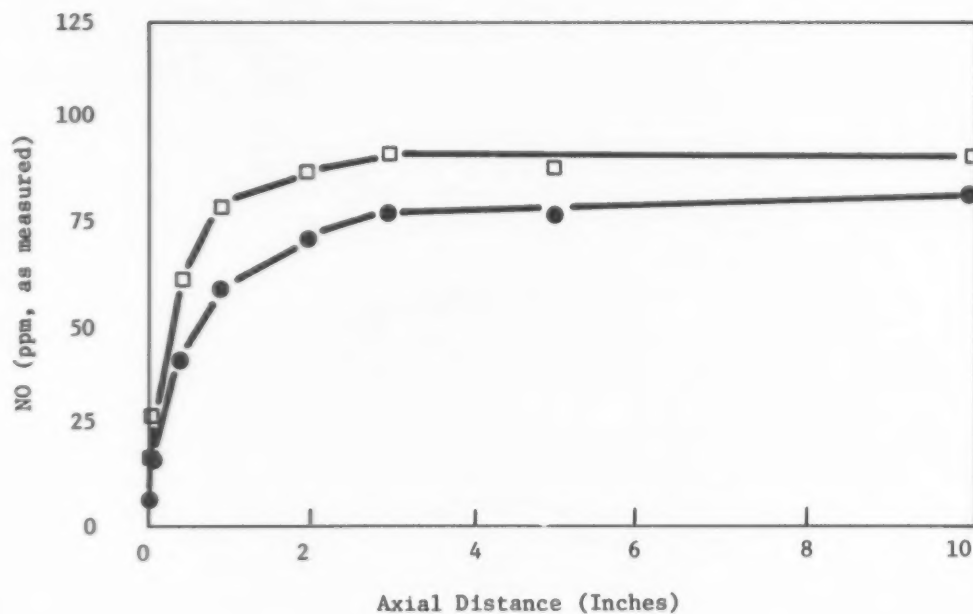
Run Number 110, Stabilized Diffusion Flame Burner (Laminar), Methane Fuel, 145% Stoichiometric Air, Cold Wall



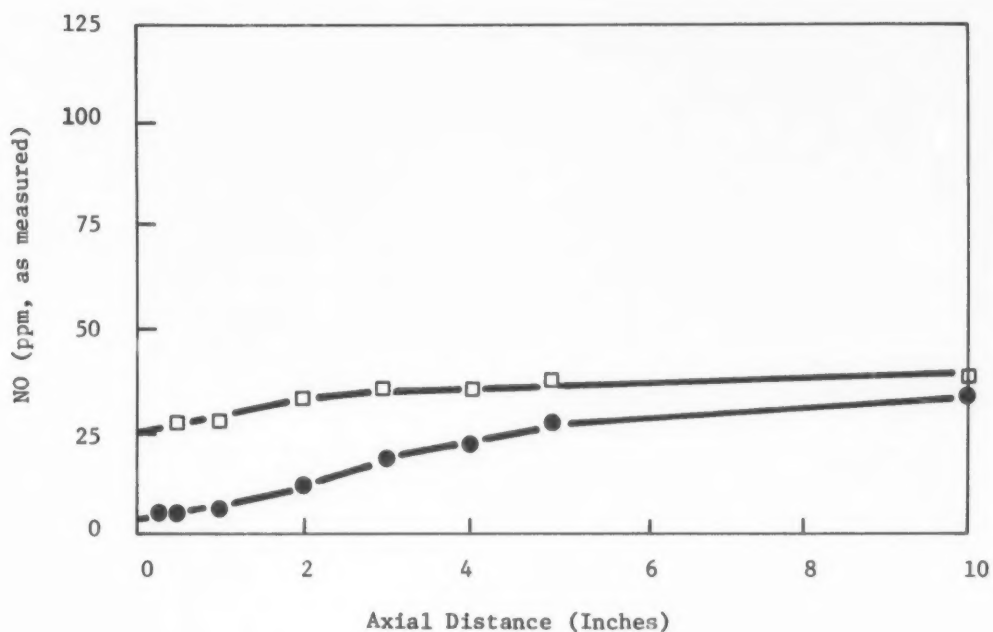
Run Number 110, Stabilized Diffusion Flame Burner (Laminar), Methane Fuel, 86% Stoichiometric Air, Cold Wall



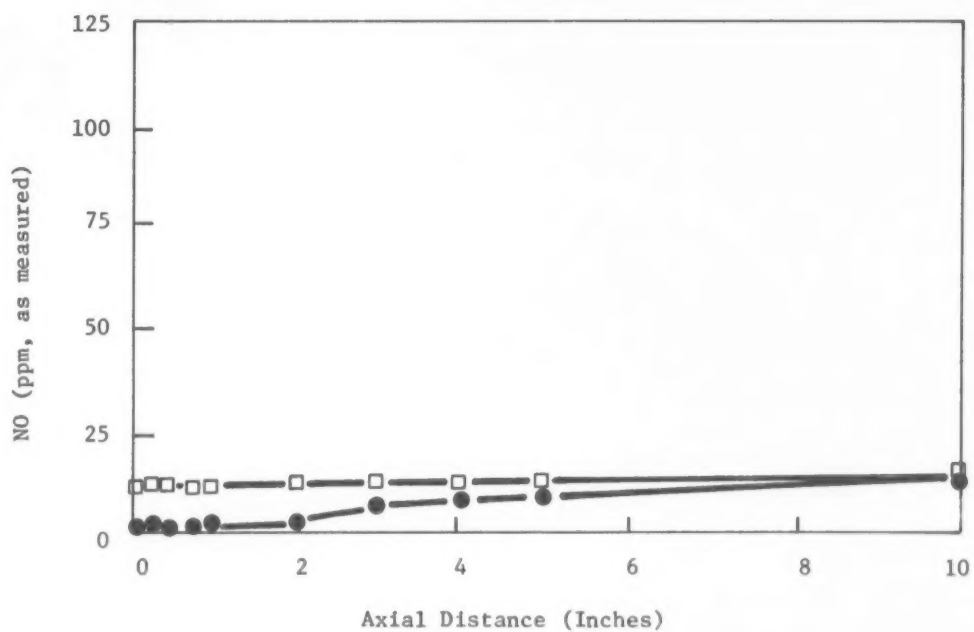
Run Number 111, Premixed Flat Flame Burner (Laminar), Methane Fuel, 104% Stoichiometric Air, Cold Wall



Run Number 112, Premixed Furnace Burner (Turbulent), Methane Fuel,
96% Stoichiometric Air, Cold Wall

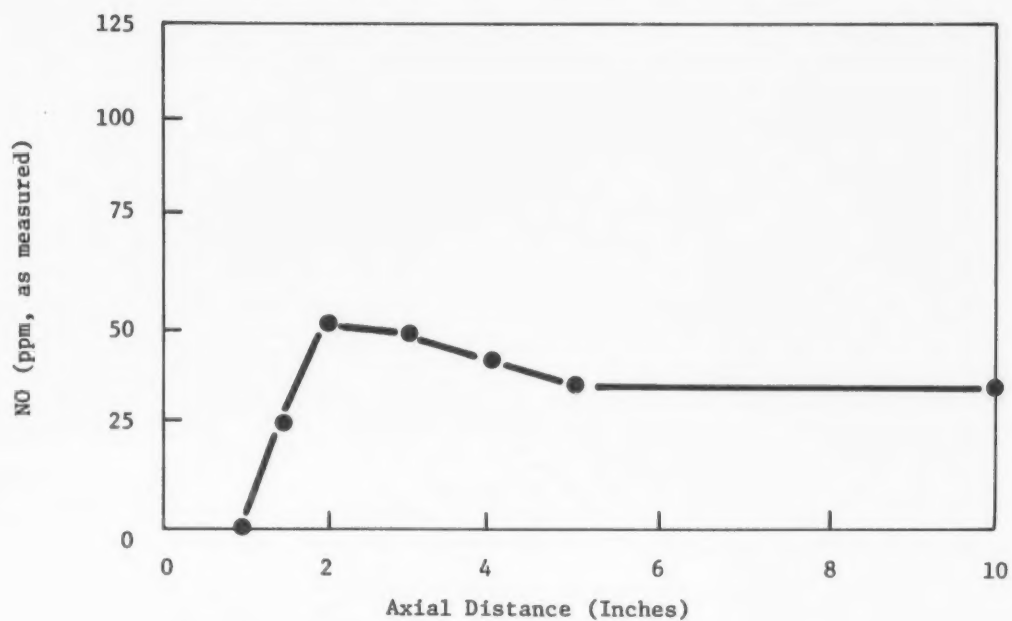


Run Number 113, Premixed Furnace Burner (Turbulent), Methane Fuel,
115% Stoichiometric Air, Cold Wall

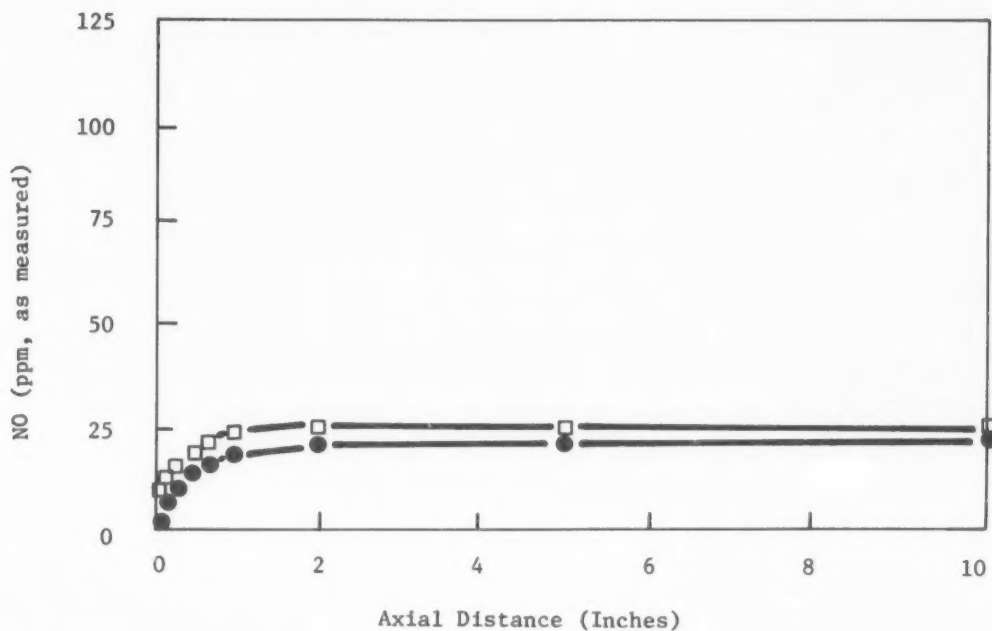


D-9

Run Number 114, Premixed Furnace Burner (Turbulent), Methane Fuel,
76% Stoichiometric Air, Cold Wall

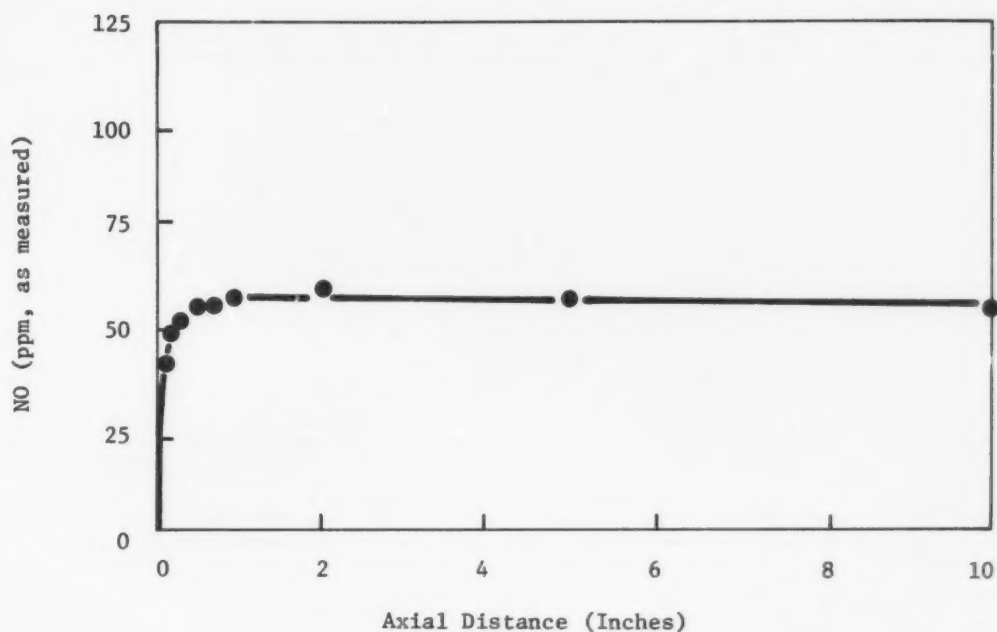


Run Number 116, Premixed Flat Flame Burner (Laminar), Methane Fuel,
119% Stoichiometric Air, Cold Wall

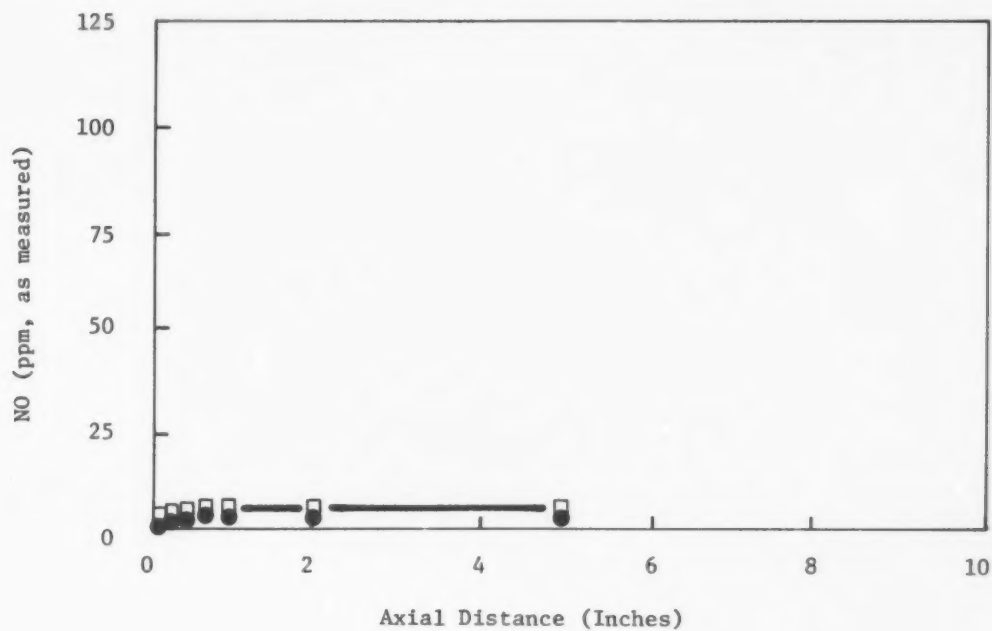


D-10

Run Number 116, Premixed Flat Flame Burner (Laminar), Methane Fuel,
80% Stoichiometric Air, Cold Wall

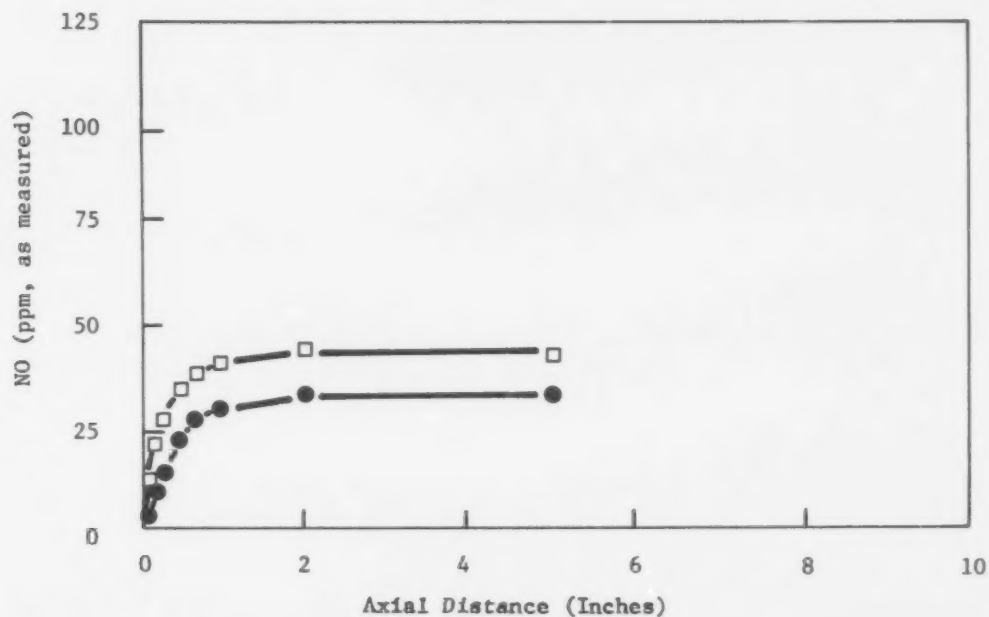


Run Number 117, Premixed Flat Flame Burner (Laminar), Methane Fuel,
161% Stoichiometric Air, Hot Wall 1430C

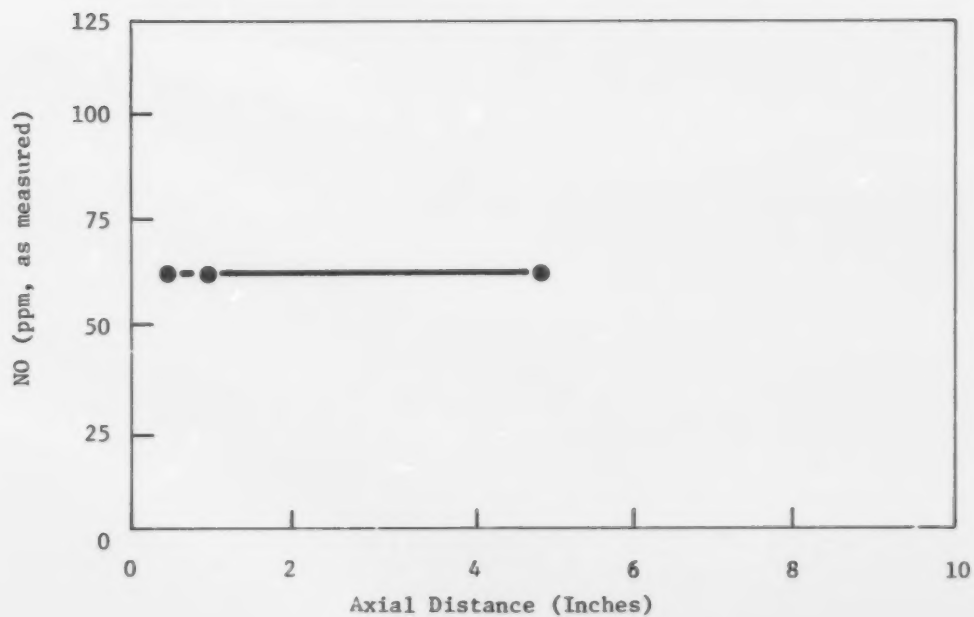


D-11

Run Number 117, Premixed Flat Flame Burner (Laminar), Methane Fuel,
119% Stoichiometric Air, Hot Wall 1430C

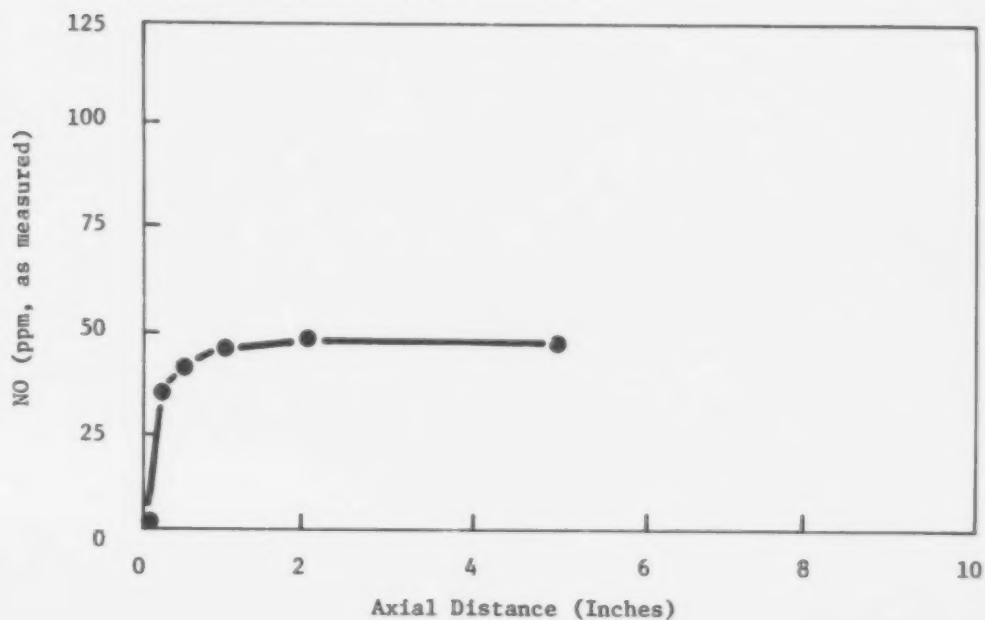


Run Number 117, Premixed Flat Flame Burner (Laminar), Methane Fuel,
80% Stoichiometric Air, Hot Wall 1825C

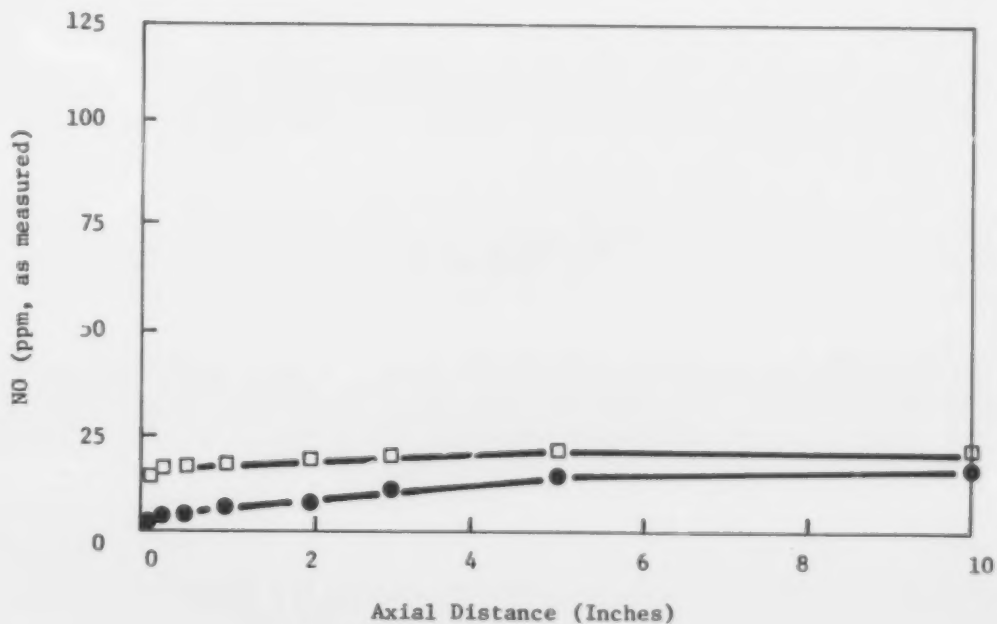


D-12

Run Number 118, Premixed Flat Flame Burner (Laminar), Propane Fuel,
61% Stoichiometric Air, Hot Wall 1565C

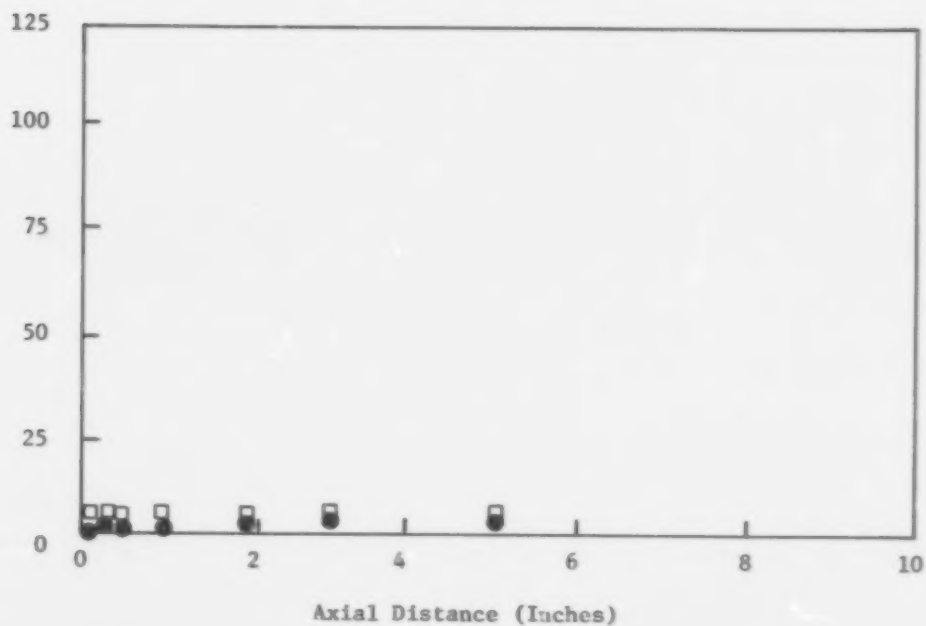


Run Number 119, Premixed Flat Flame Burner (Turbulent), Propane
Fuel, 110% Stoichiometric Air, Cold Wall

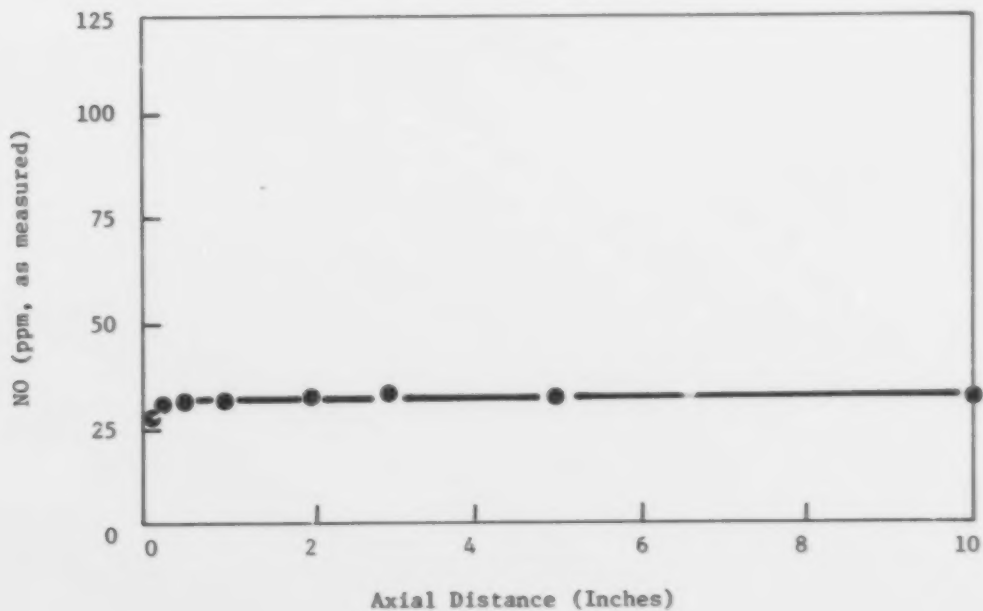


D-13

Run Number 119, Premixed Flat Flame Burner (Turbulent), Propane
Fuel, 132% Stoichiometric Air, Cold Wall

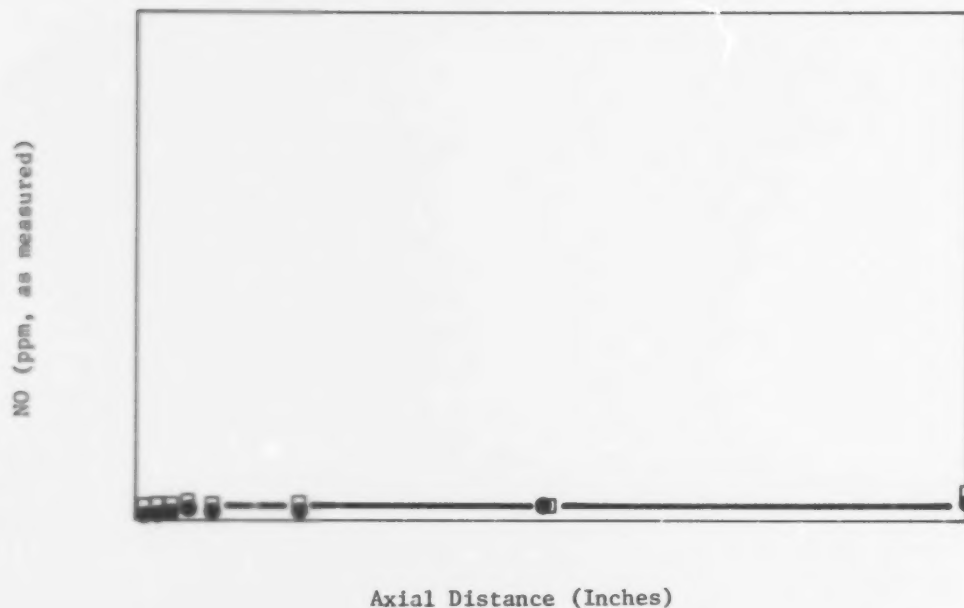


Run Number 119, Premixed Flat Flame Burner (Turbulent), Propane
Fuel, 88% Stoichiometric Air, Cold Wall

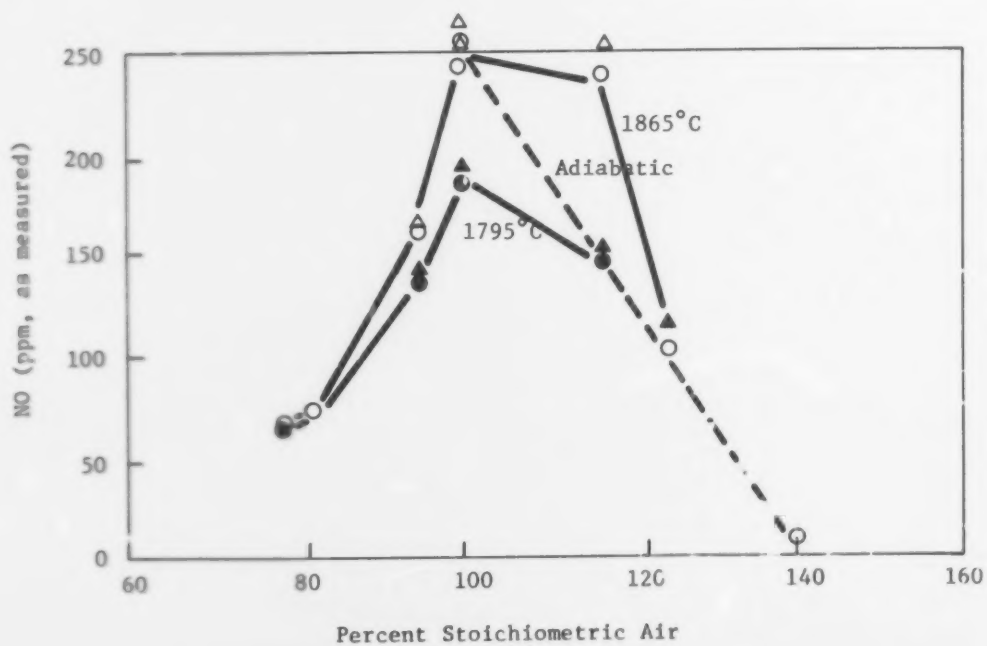


D-14

Run Number 120, Premixed Furnace Burner (Laminar), Propane Fuel,
156% Stoichiometric Air, Hot Wall 1495C

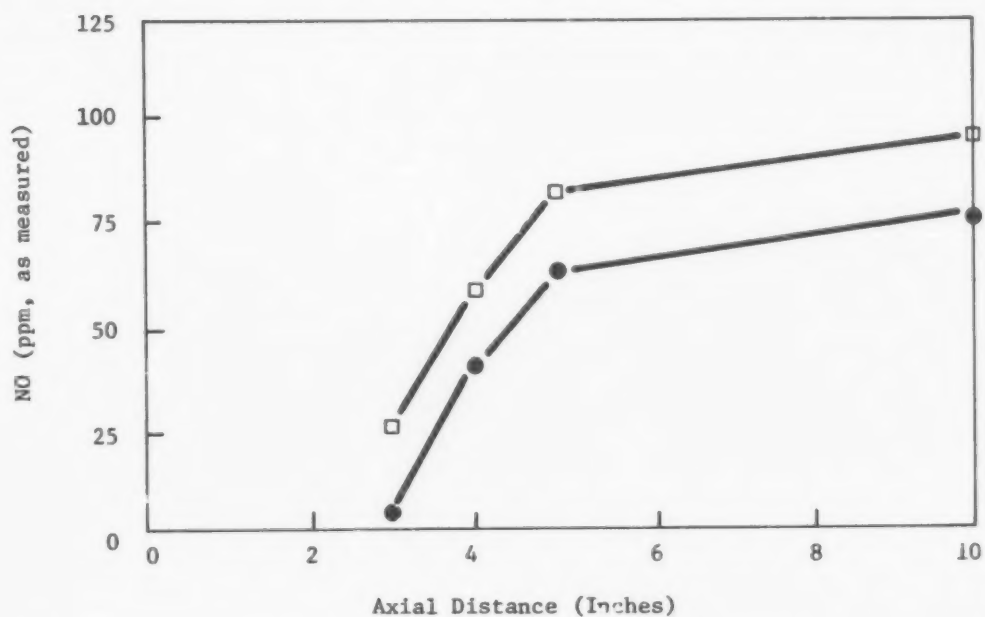


Run Number 121, Premixed Furnace Burner (Laminar), Propane Fuel,
Stoichiometric Air, Hot Wall

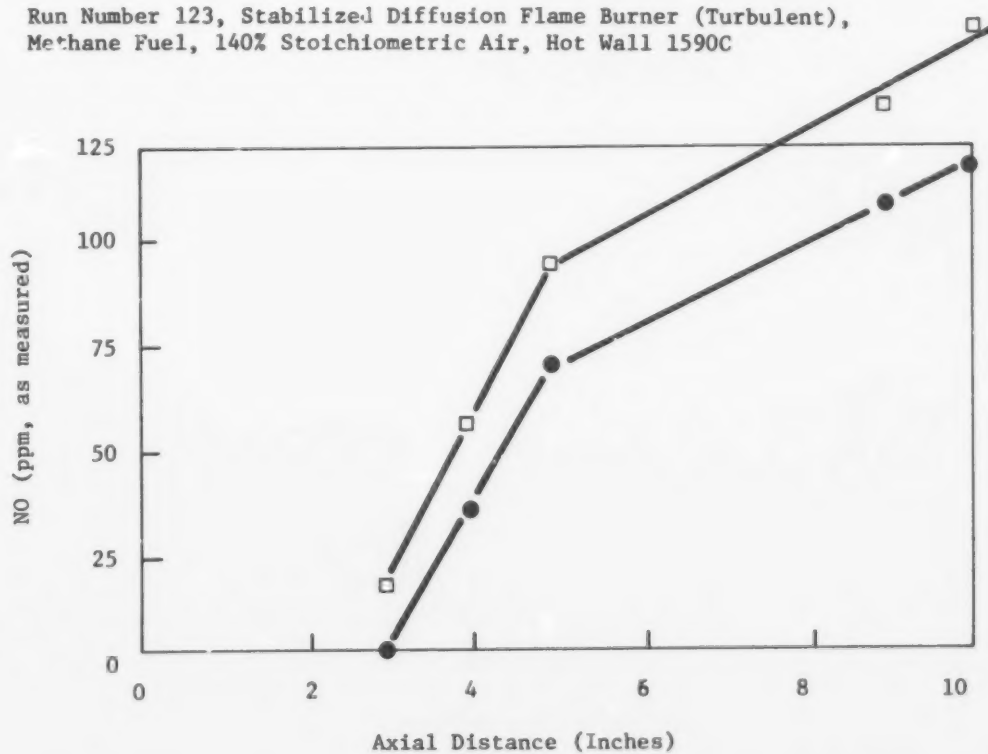


D-15

Run Number 122, Stabilized Diffusion Flame Burner (Turbulent),
Methane Fuel, 160% Stoichiometric Air, Hot Wall 1450C

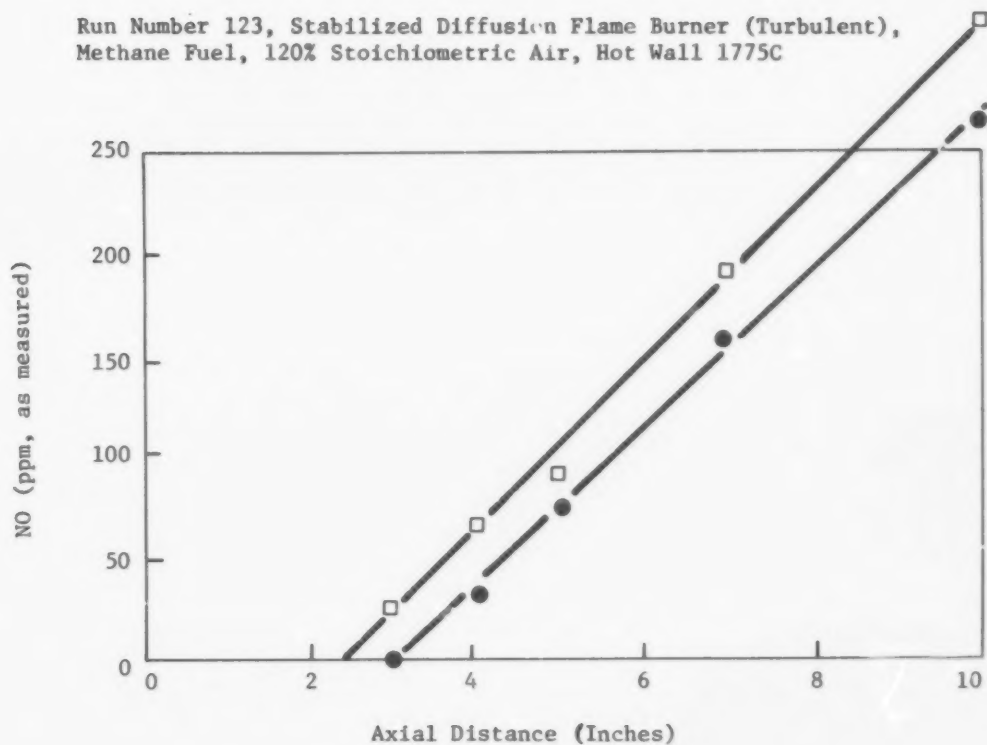


Run Number 123, Stabilized Diffusion Flame Burner (Turbulent),
Methane Fuel, 140% Stoichiometric Air, Hot Wall 1590C

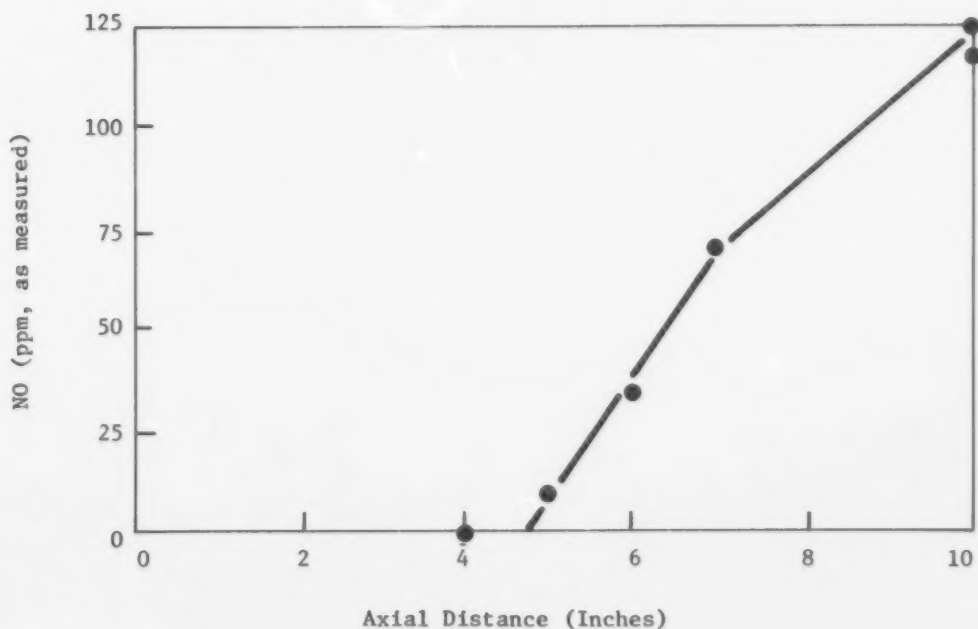


D-16

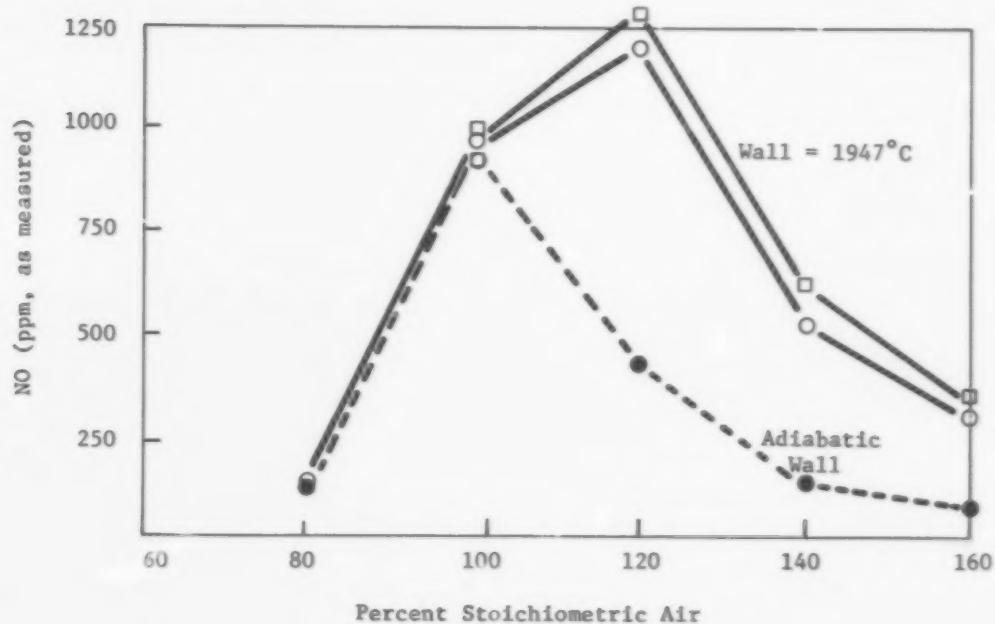
Run Number 123, Stabilized Diffusion Flame Burner (Turbulent),
Methane Fuel, 120% Stoichiometric Air, Hot Wall 1775C



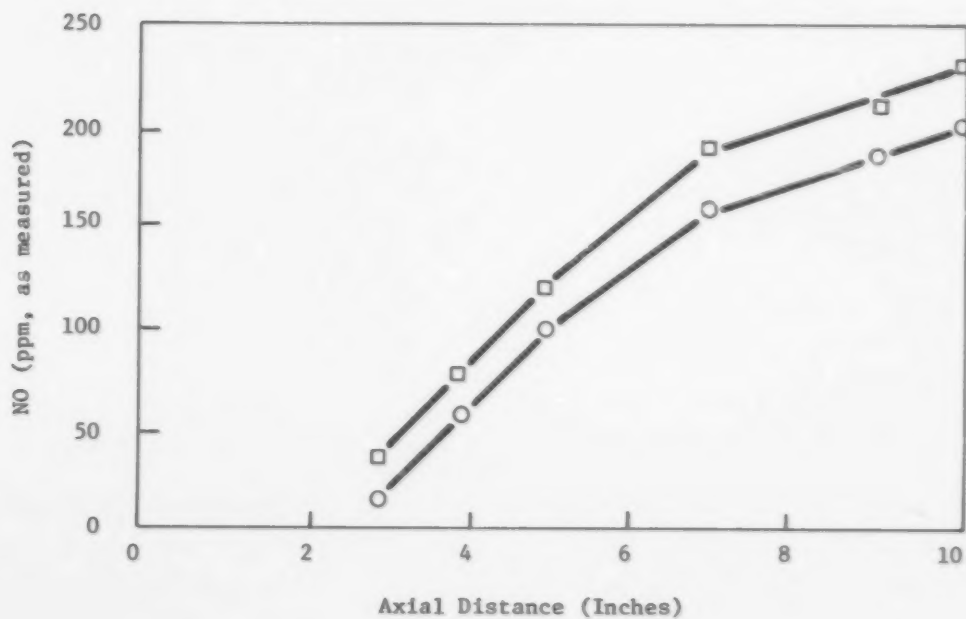
Run Number 123, Stabilized Diffusion Flame Burner (Turbulent),
Methane Fuel, 80% Stoichiometric Air, Hot Wall 1825C



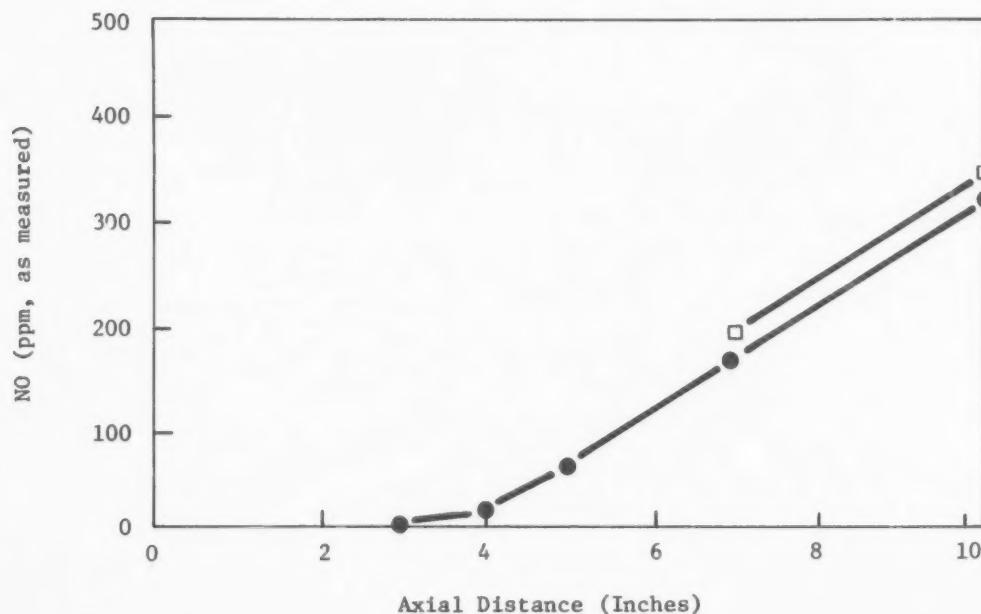
Run Number 124, Stabilized Diffusion Flame Burner (Turbulent),
Methane Fuel, Stoichiometric Air, Hot Wall



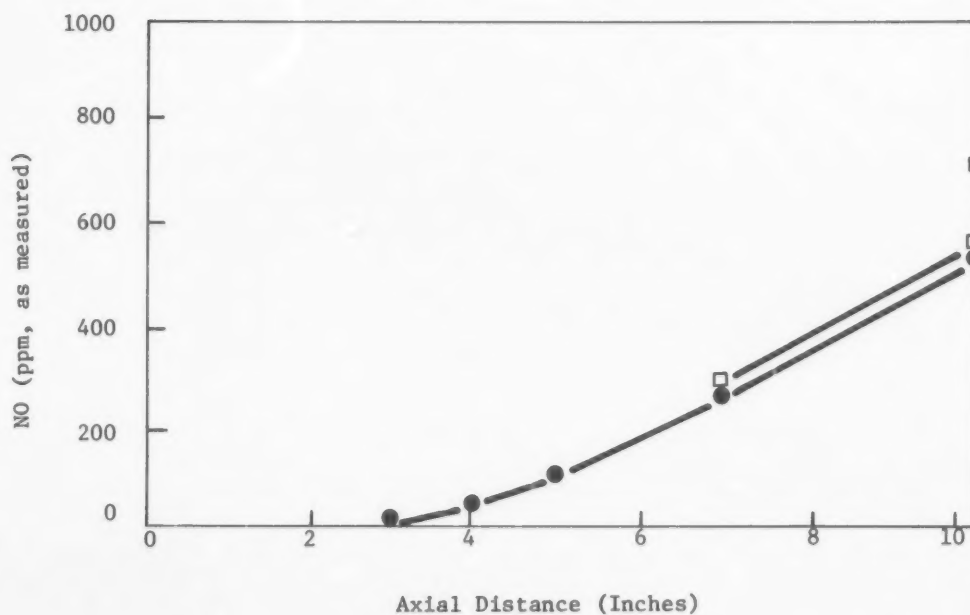
Run Number 125, Stabilized Diffusion Flame Burner (Turbulent),
Propane Fuel, 160% Stoichiometric Air, Hot Wall 1425C



Run Number 126, Stabilized Diffusion Flame Burner (Turbulent),
Propane Fuel, 141% Stoichiometric Air, Hot Wall 1610C

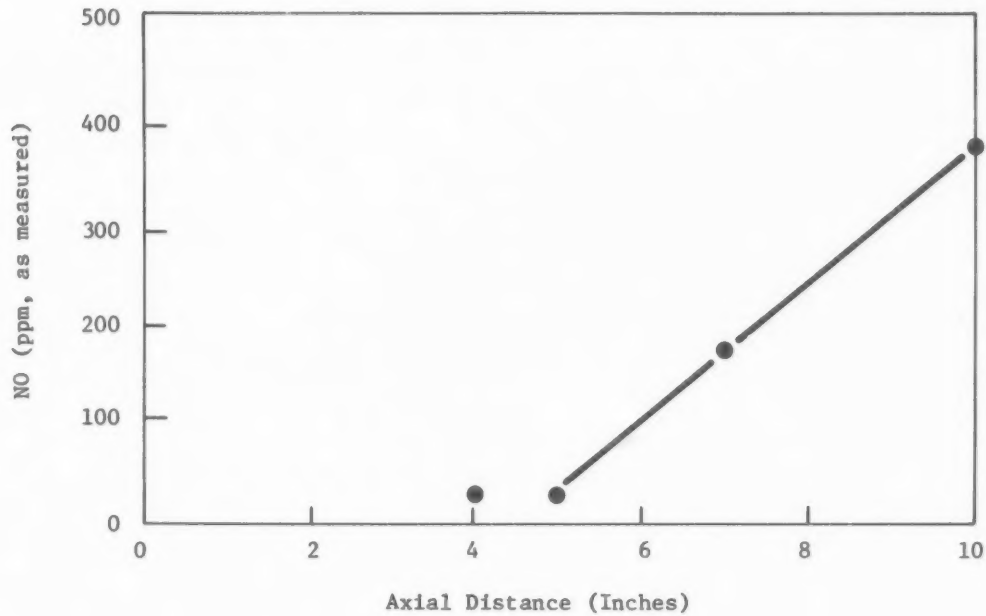


Run Number 127, Stabilized Diffusion Flame Burner (Turbulent),
Propane Fuel, 114% Stoichiometric Air, Hot Wall 1870C

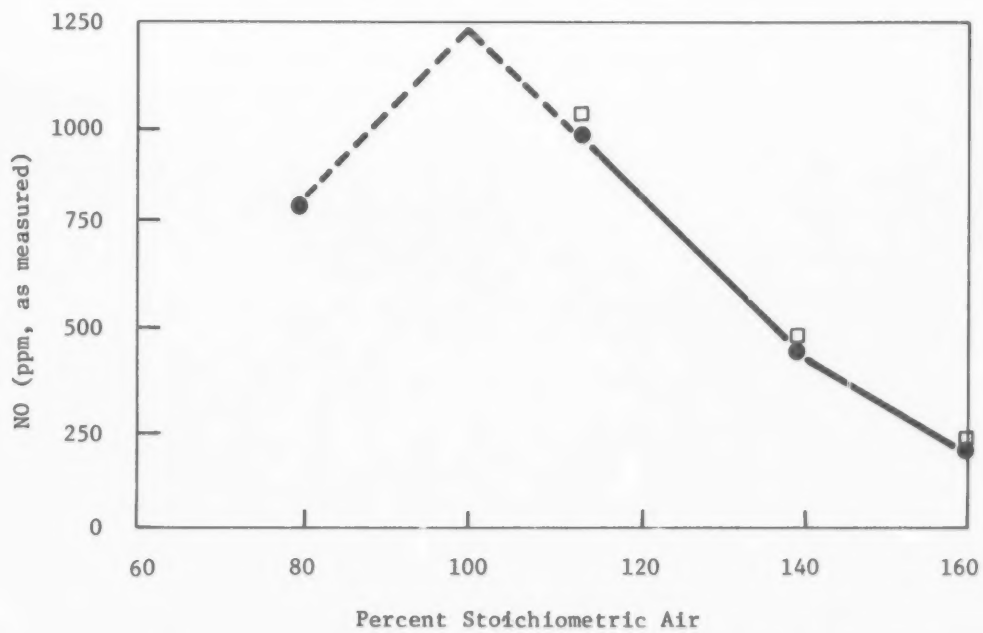


D-19

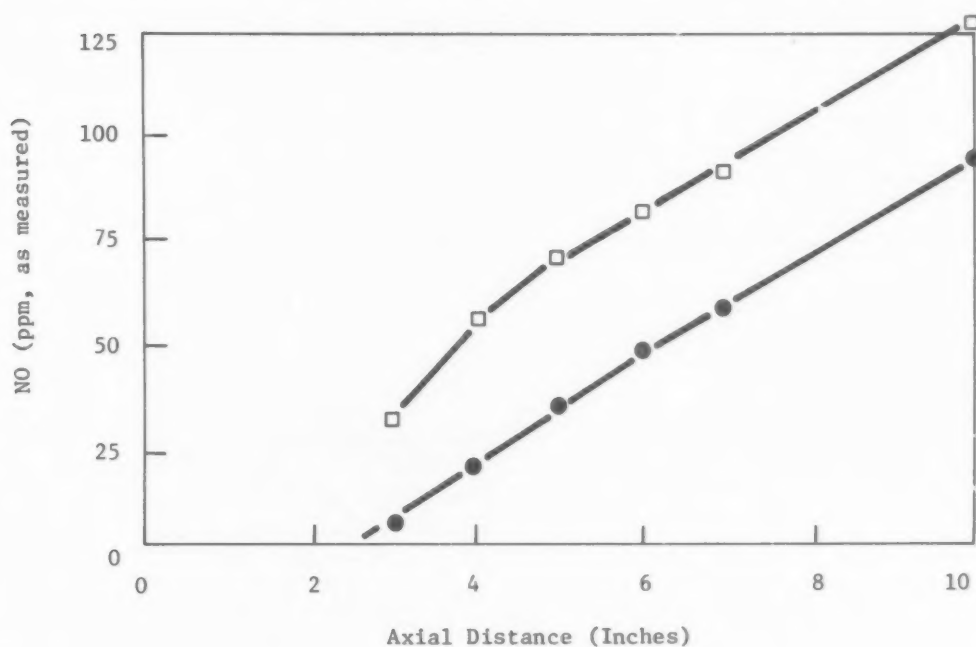
Run Number 127, Stabilized Diffusion Flame Burner (Turbulent),
Propane Fuel, 80% Stoichiometric Air, Hot Wall 1870C



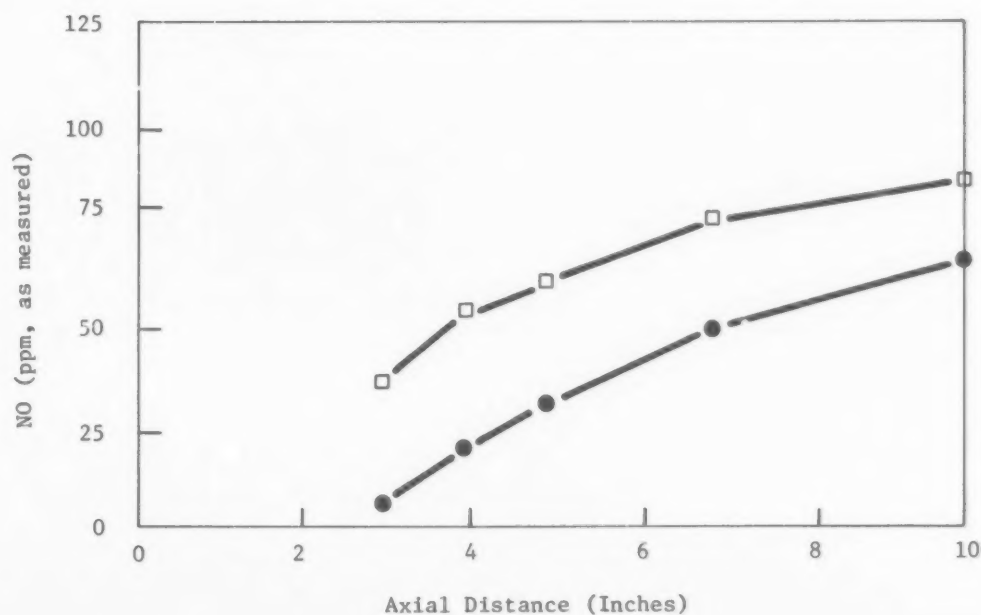
Run Number 127, Stabilized Diffusion Flame Burner (Turbulent),
Propane Fuel, Stoichiometric Air, Hot Wall



Run Number 128, Stabilized Diffusion Flame Burner (Turbulent),
Methane Fuel, 140% Stoichiometric Air, Hot Wall 1590C

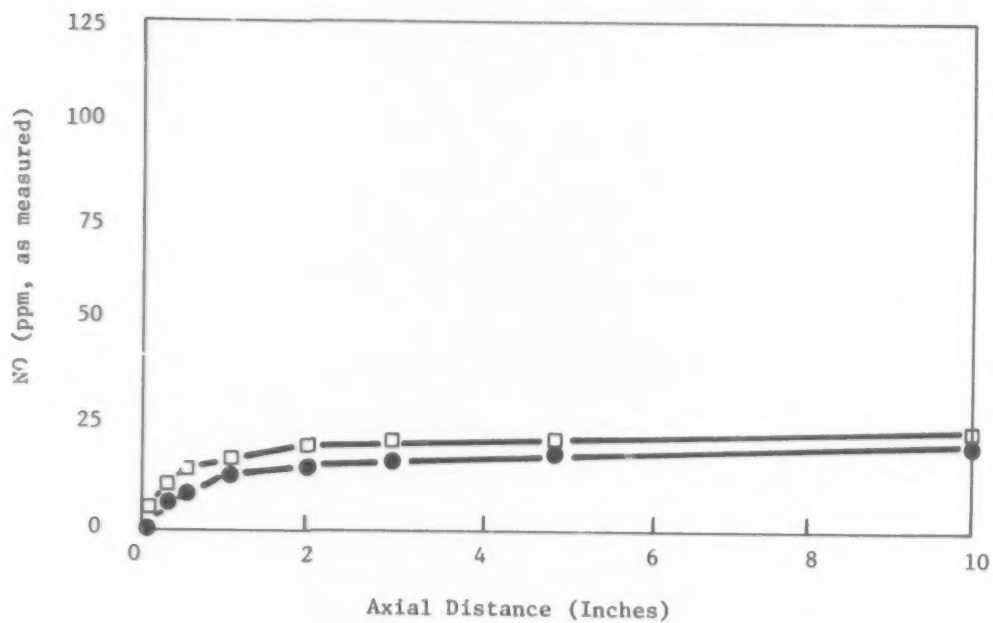


Run Number 128, Stabilized Diffusion Flame Burner (Turbulent),
Methane Fuel, 160% Stoichiometric Air, Hot Wall 1440C

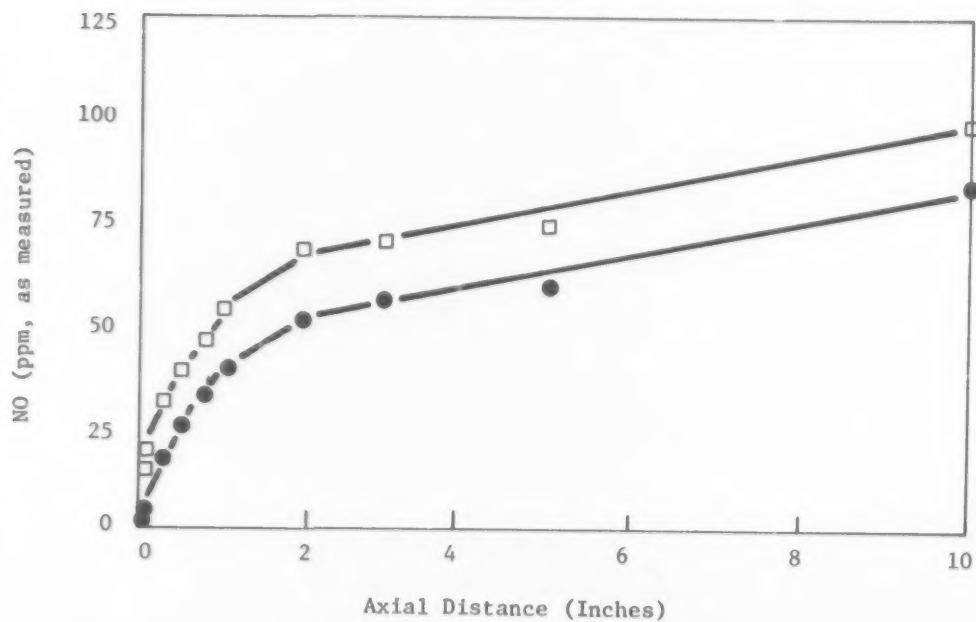


D-21

Run Number 130, Premixed Flat Flame Burner (Laminar), Methane
Fuel, 140% Stoichiometric Air, Hot Wall 1585C

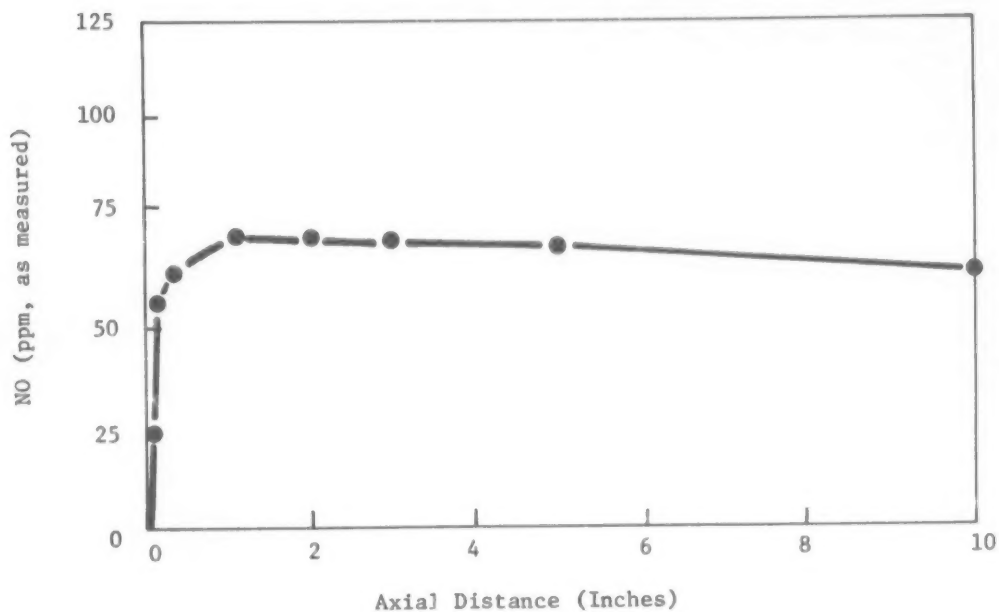


Run Number 131, Premixed Flat Flame Burner (Laminar), Methane
Fuel, 120% Stoichiometric Air, Hot Wall 1770C

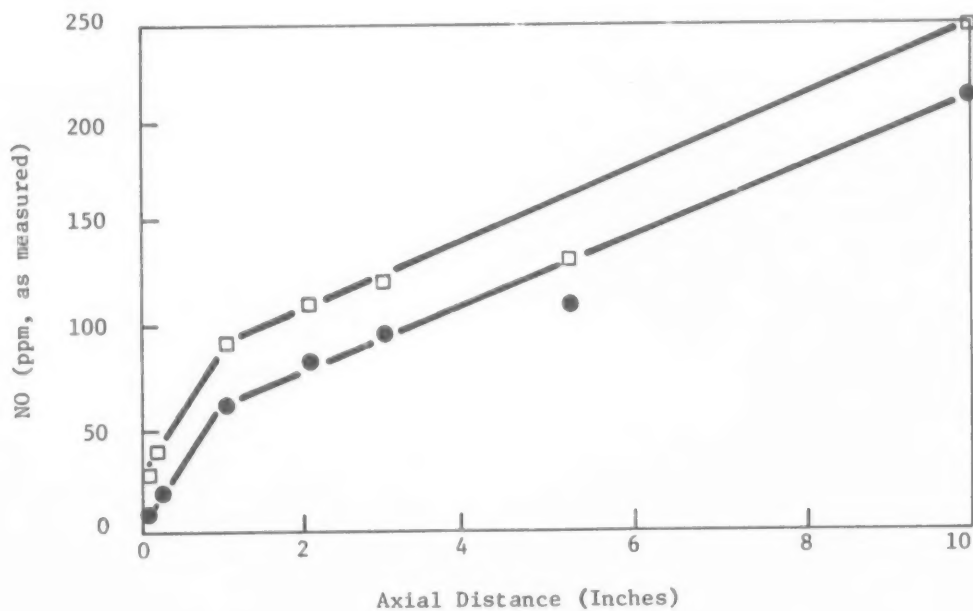


D-22

Run Number 131, Premixed Flat Flame Burner (Laminar), Methane
Fuel, 78% Stoichiometric Air, Hot Wall 1770C

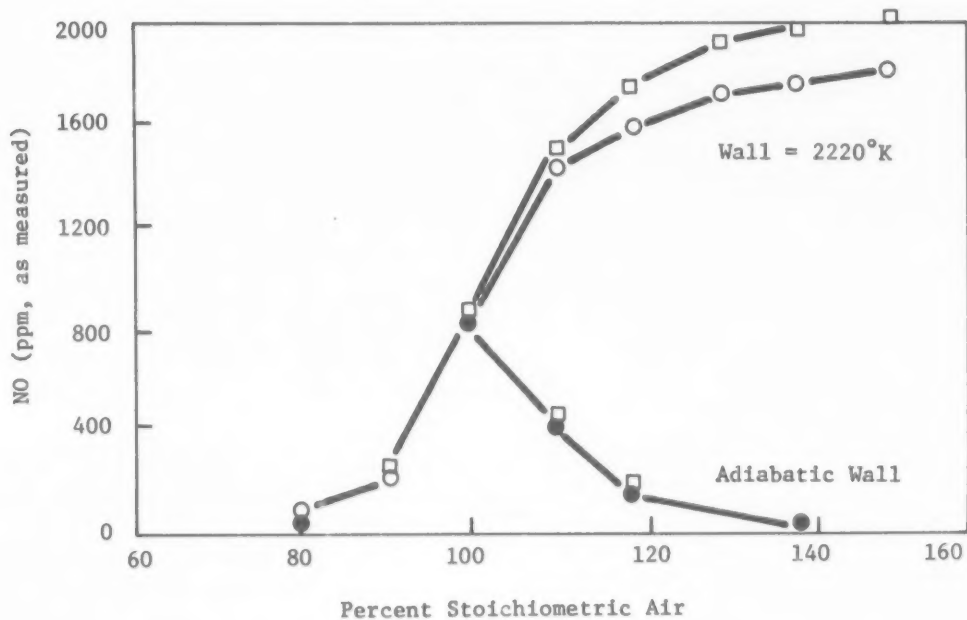


Run Number 131, Premixed Flat Flame Burner (Laminar), Methane
Fuel, 111% Stoichiometric Air, Hot Wall 1865C

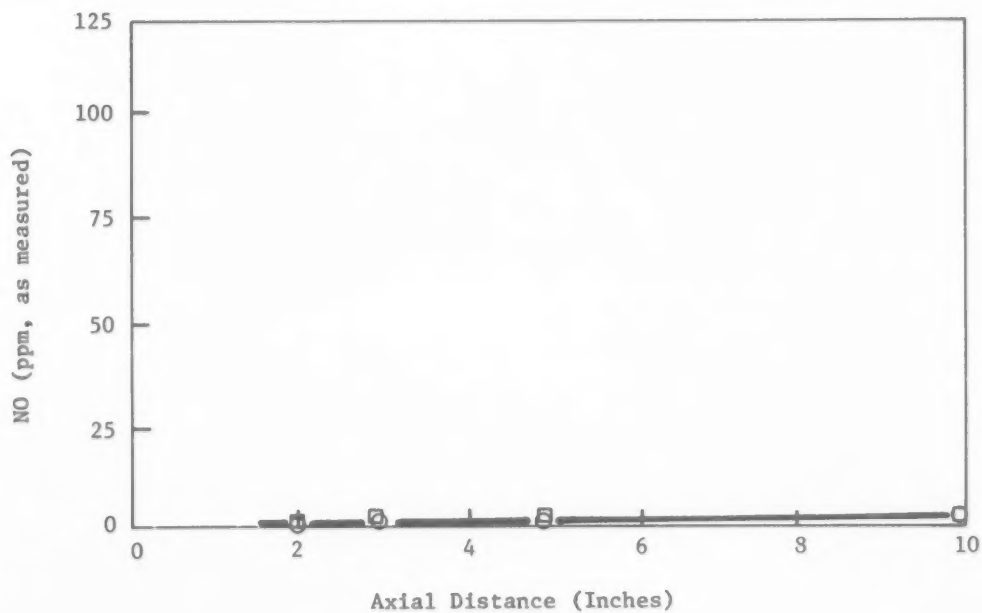


D-23

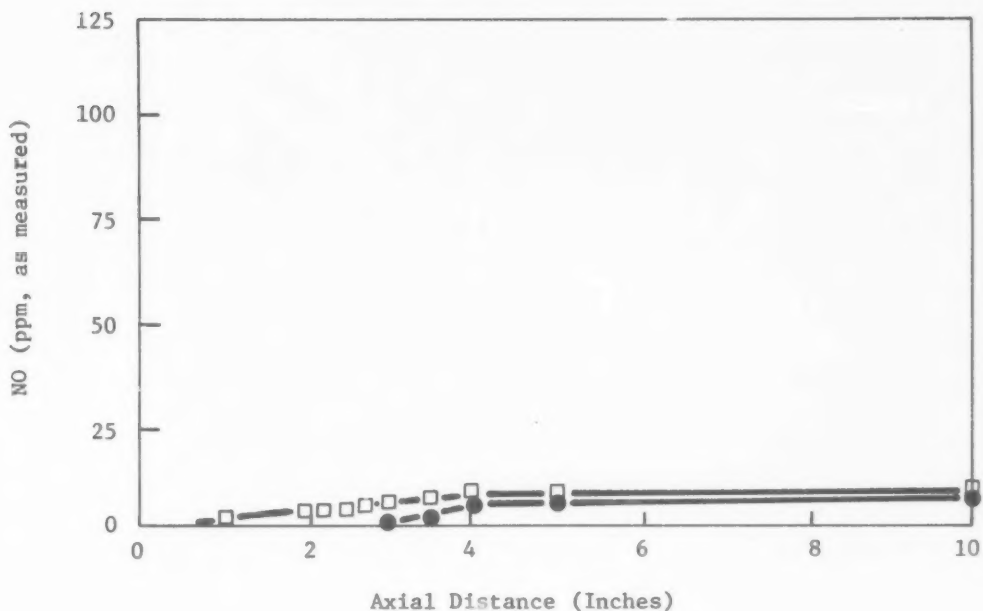
Run Number 131, Premixed Flat Flame Burner (Laminar), Methane Fuel, Stoichiometric Air, Hot Wall



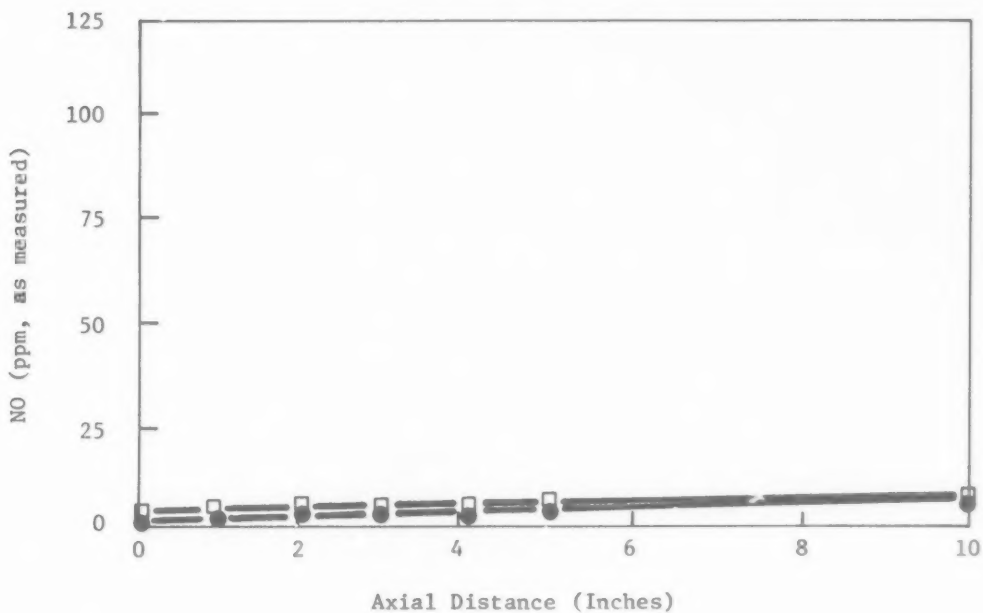
Run Number 132, Premixed Furnace Burner (Laminar), Methane Fuel, 160% Stoichiometric Air, Hot Wall 1440C



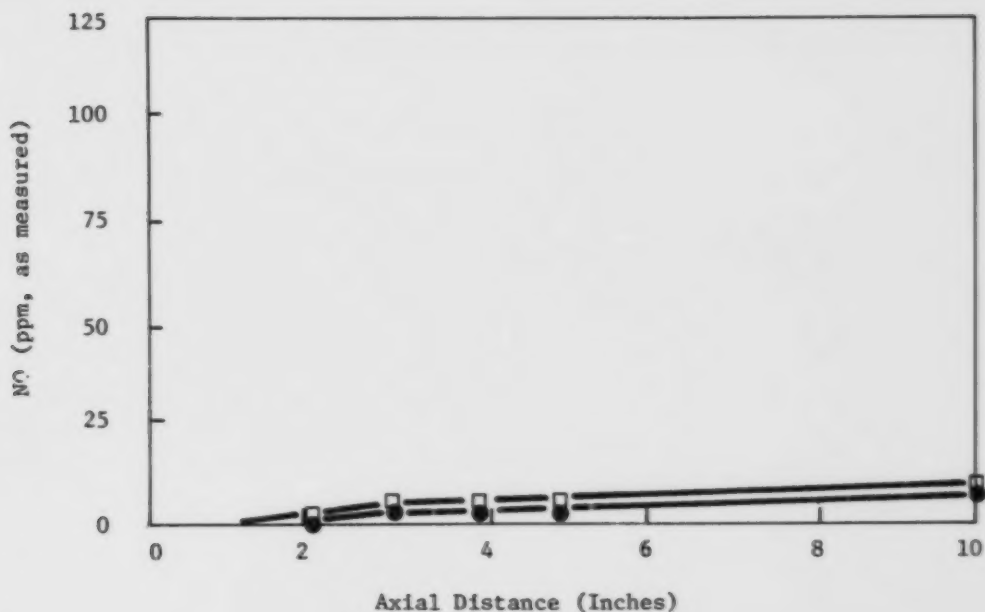
Run Number 133, Premixed Furnace Burner (Turbulent), Methane Fuel, 140% Stoichiometric Air, Hot Wall 1590C



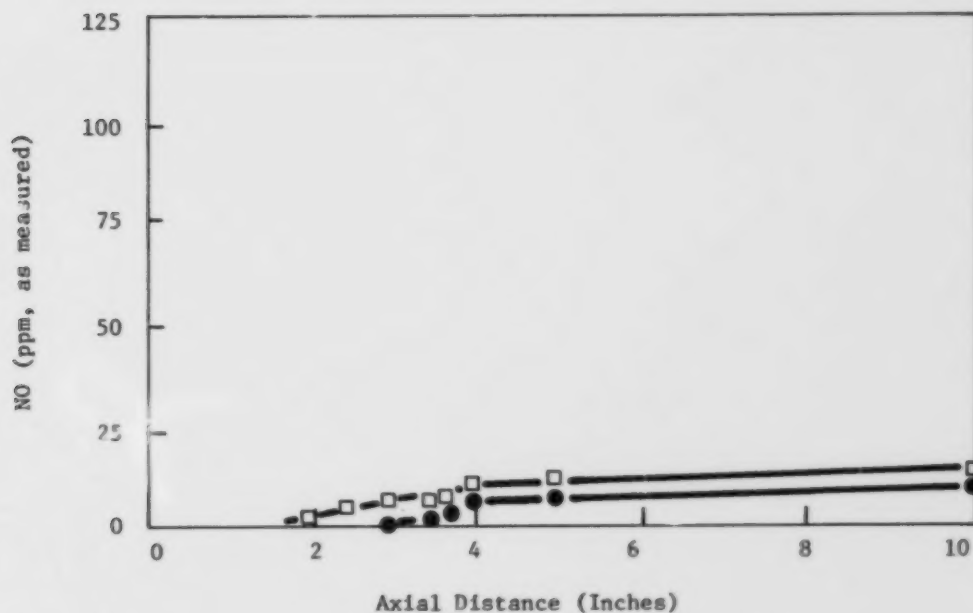
Run Number 134, Premixed Furnace Burner (Laminar), Methane Fuel, 140% Stoichiometric Air, Hot Wall 1585C



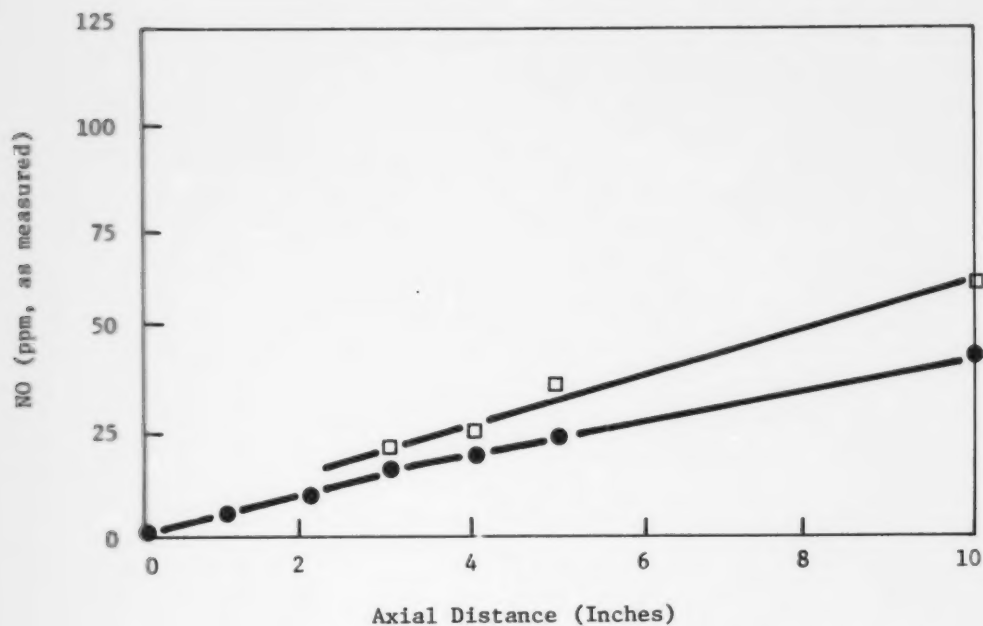
Run Number 135, Premixed Furnace Burner (Laminar), Propane Fuel,
139% Stoichiometric Air, Hot Wall 1625C



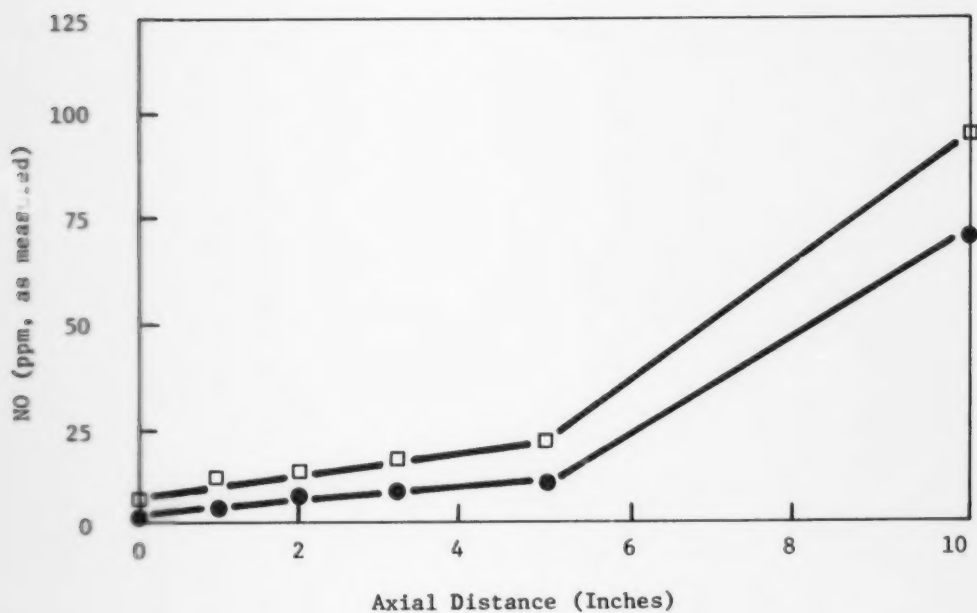
Run Number 136, Premixed Furnace Burner (Turbulent), Propane
Fuel, 141% Stoichiometric Air, Hot Wall 1610C



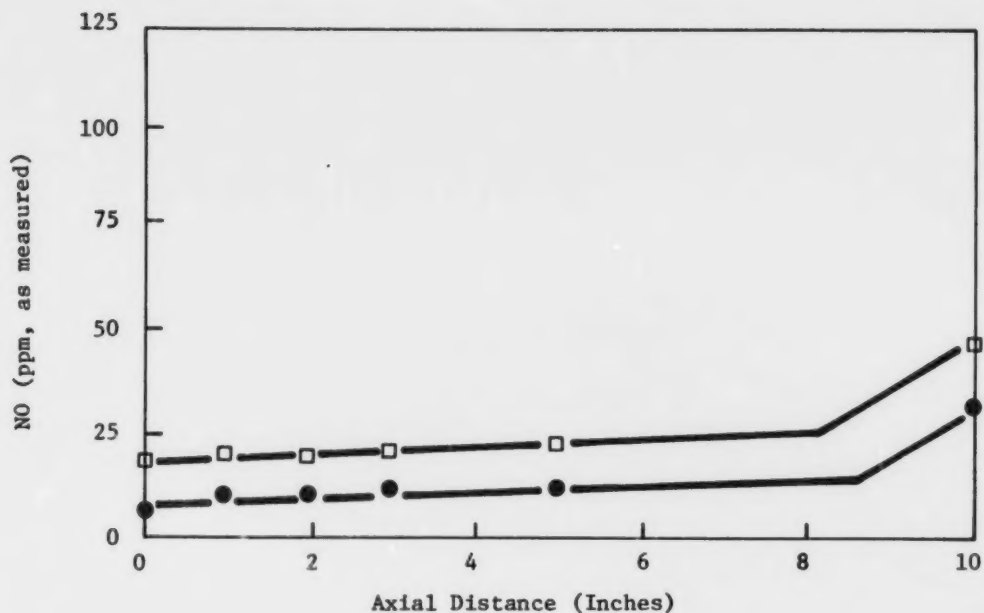
Run Number 137, Premixed Furnace Burner (Turbulent), Propane Fuel, 121% Stoichiometric Air, Hot Wall 1795C



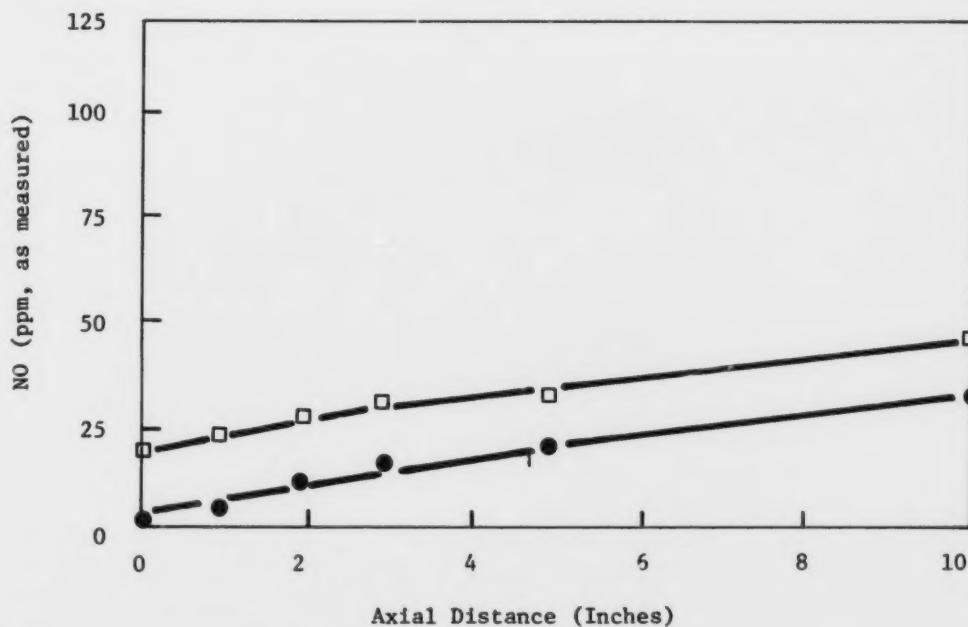
Run Number 138, Premixed Furnace Burner (Laminar), Propane Fuel 121% Stoichiometric Air, Hot Wall 1795C



Run Number 139, Premixed Furnace Burner (Laminar), Methane Fuel,
120% Stoichiometric Air, Hot Wall 1770C

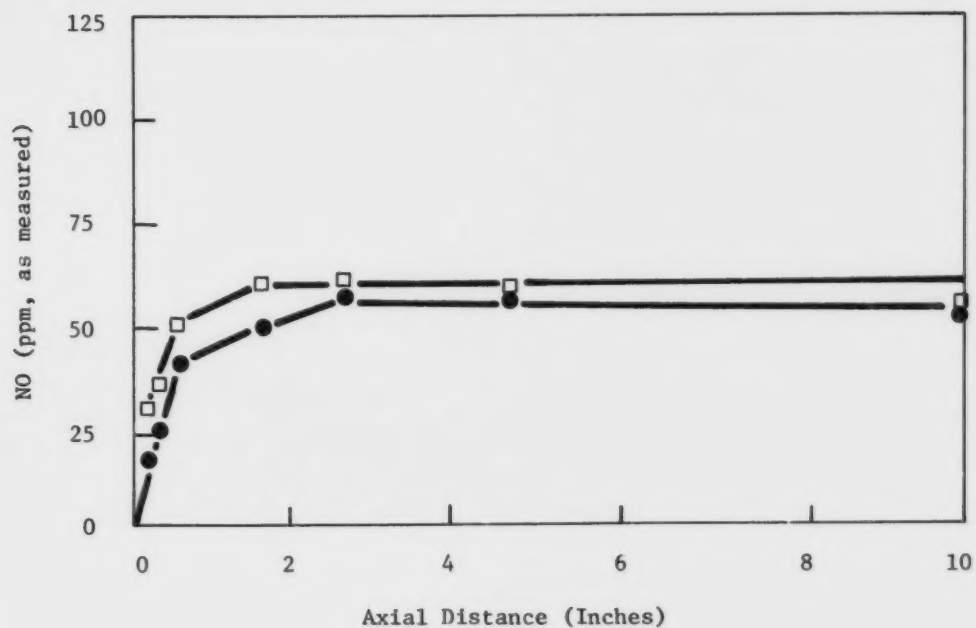


Run Number 140, Premixed Furnace Burner (Turbulent), Methane
Fuel, 120% Stoichiometric Air, Hot Wall 1775C



D-20

Run Number 141, Premixed Flat Flame Burner (Laminar), Methane
Fuel, 101% Stoichiometric Air, Cold Wall



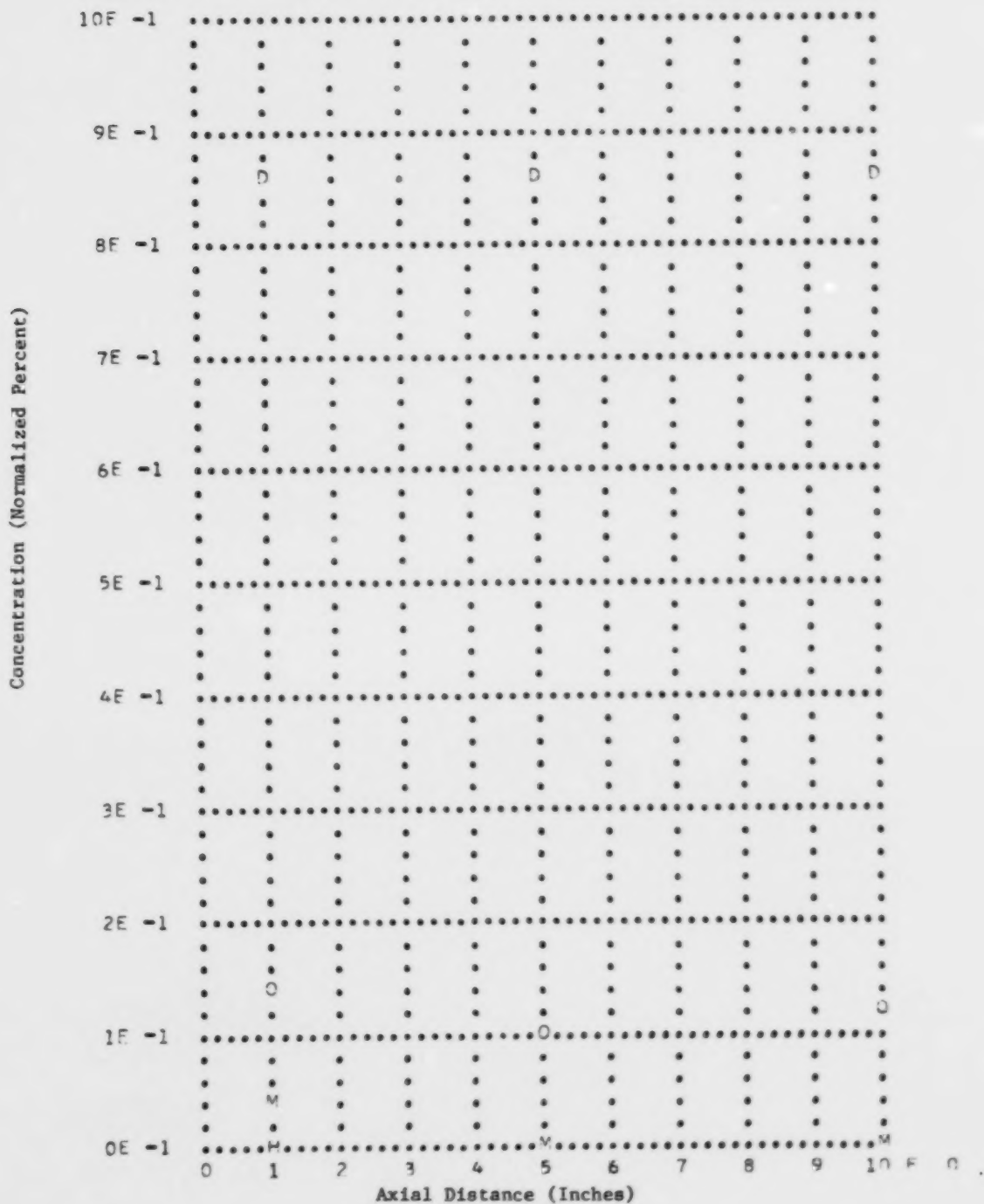
E-1
APPENDIX E

CO/CO₂/HC/O₂ DATA PLOTS

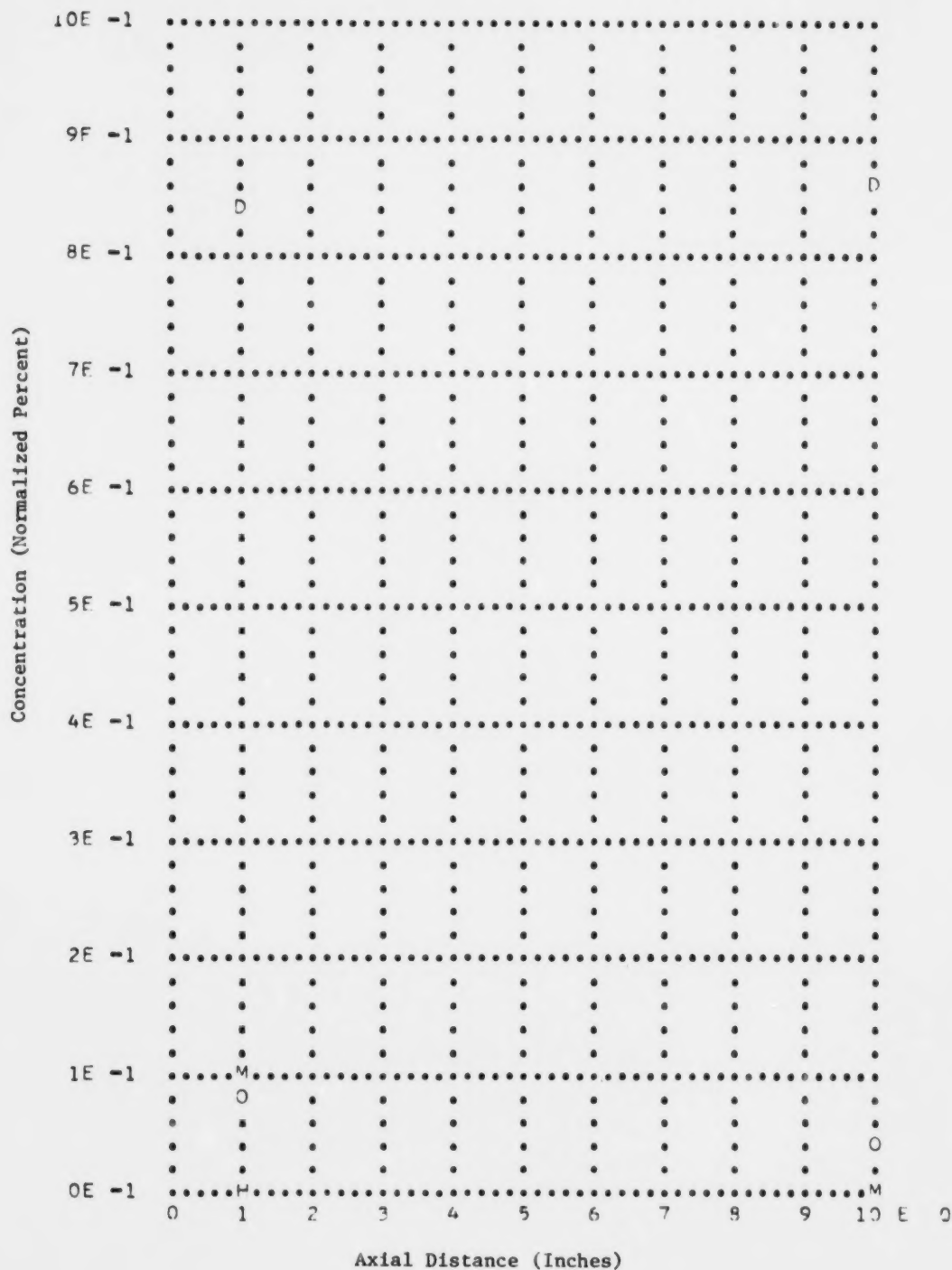
Run Number 102, Premixed Flat Flame Burner (Laminar), Propane Fuel,
106% Stoichiometric Air, Cold Wall

Normalized Species Concentrations CO₂/15, CO/5, O₂/10, HC/5

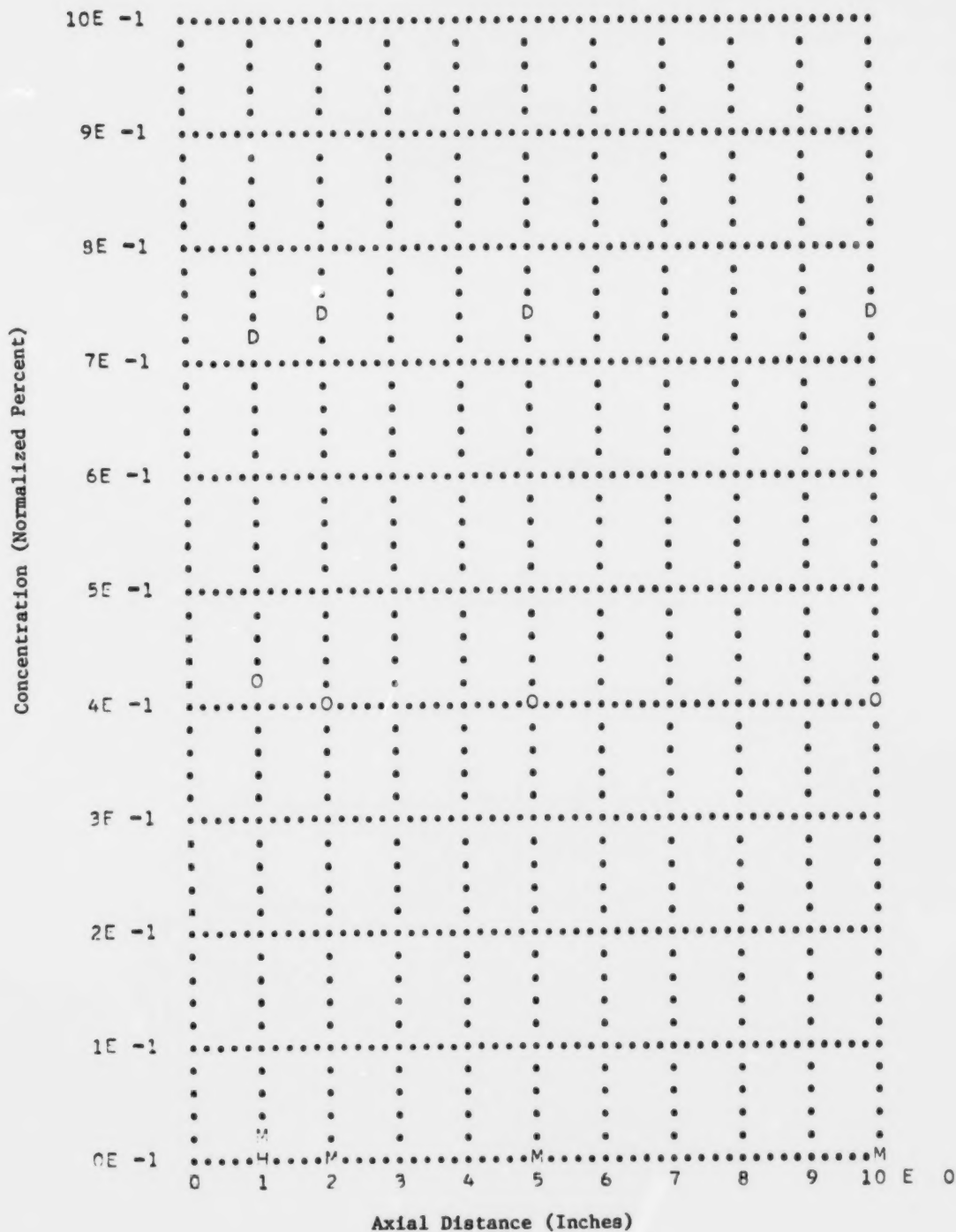
Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



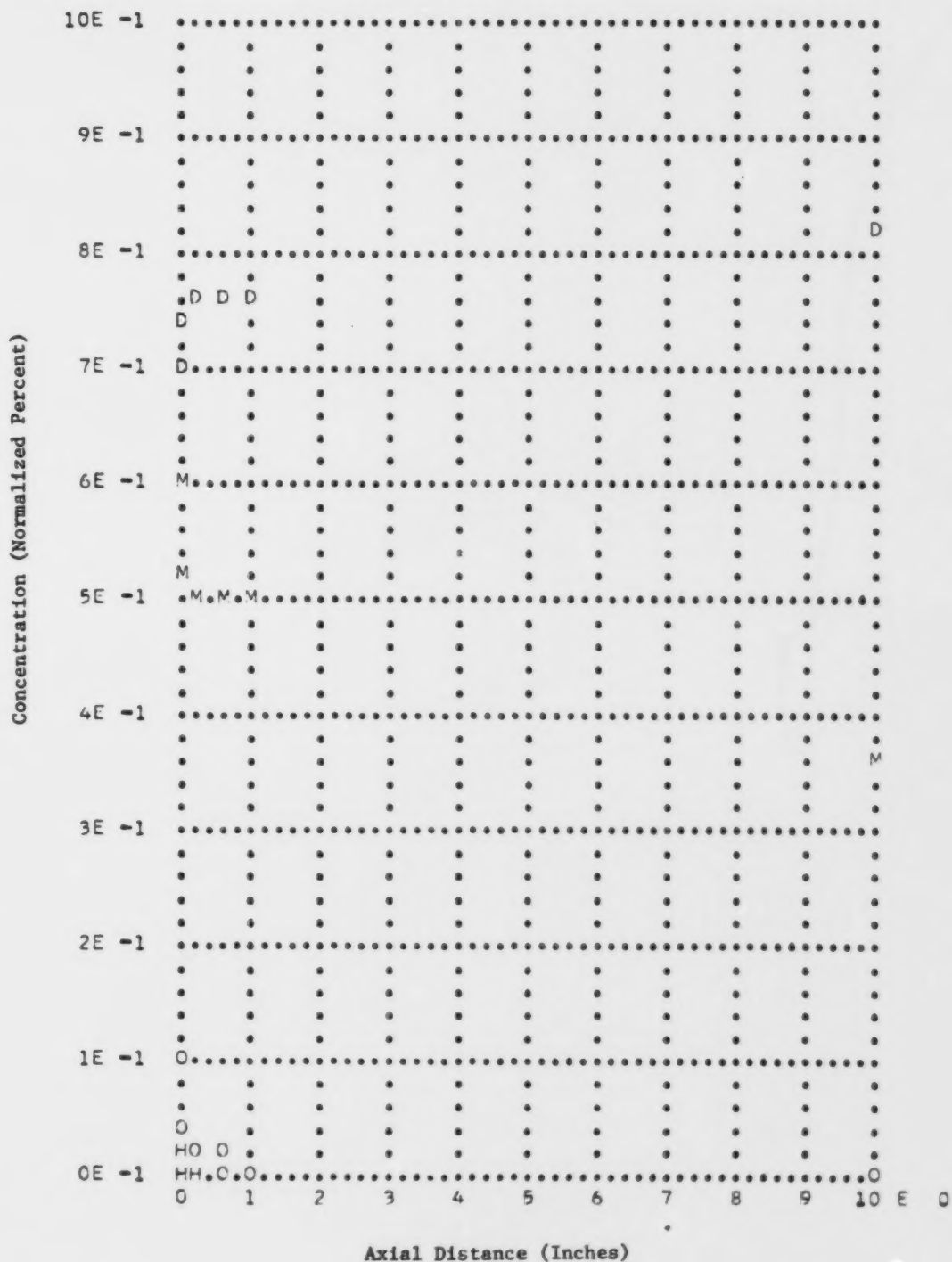
Run Number 103, Premixed Flat Flame Burner (Laminar), Propane Fuel
 103% Stoichiometric Air, Cold Wall
 Normalized Species Concentrations $\text{CO}_2/15$, $\text{CO}/5$, $\text{O}_2/10$, $\text{HC}/5$
 Legend - Carbon Dioxide = D, Carbon Monoxide = M, Oxygen = O, Hydrocarbon = H



Run Number 103, Premixed Flat Flame Burner (Laminar), Propane Fuel, 122%
 Stoichiometric Air, Cold Wall
 Normalized Species Concentrations $\text{CO}_2/15$, $\text{CO}/5$, $\text{O}_2/10$, $\text{HC}/5$
 Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H

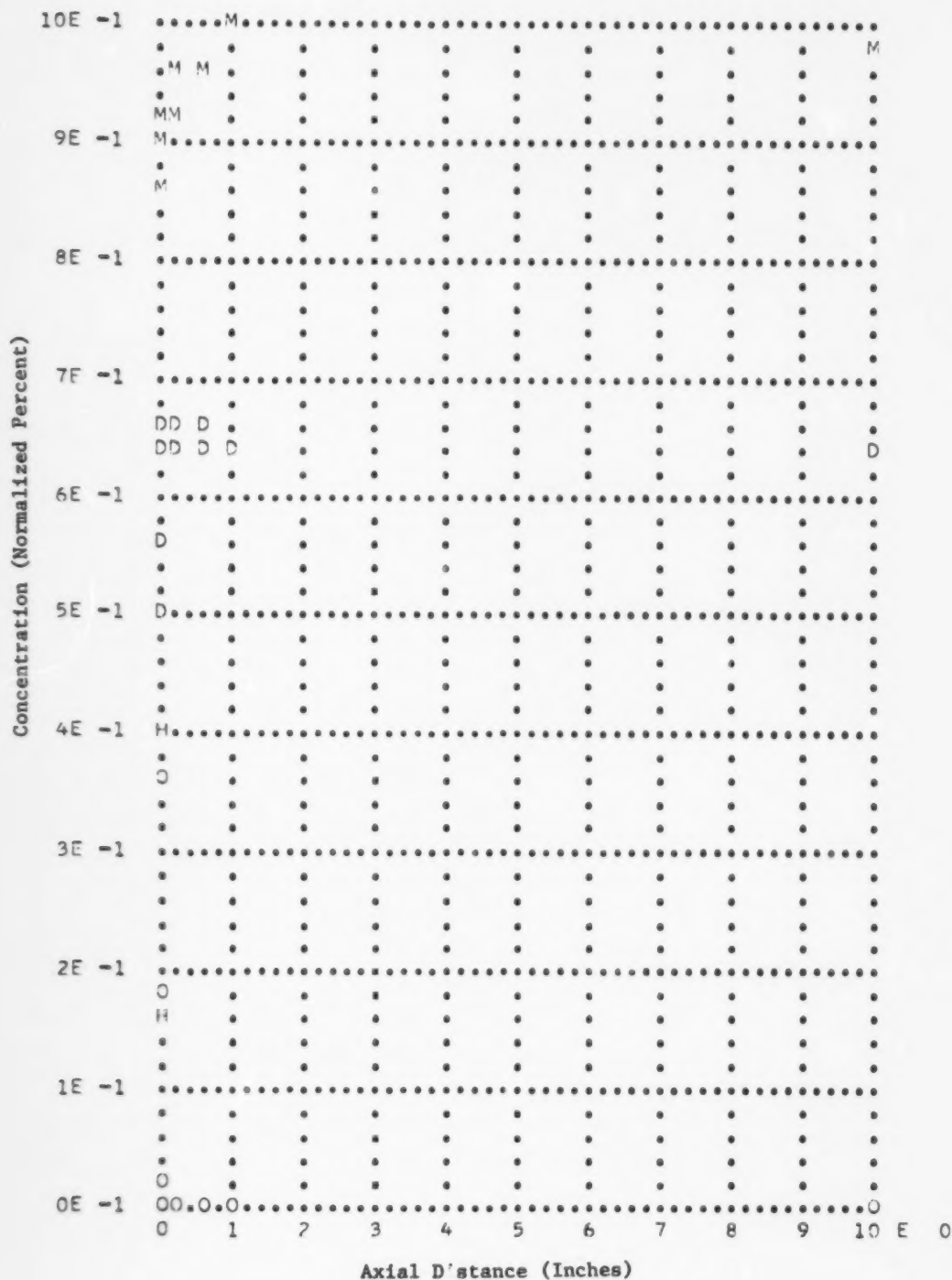


Run Number 104, Premixed Flat Flame Burner (Laminar), Propane Fuel,
 94% Stoichiometric Air, Cold Wall
 Normalized Species Concentrations CO₂/15, CO/5, O₂/10, HC/5
 Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



E-5

Run Number 104, Premixed Flat Flame Burner (Laminar), Propane Fuel,
83% Stoichiometric Air, Cold Wall
Normalized Species Concentrations CO₂/15, CO/5, O₂/10, HC/5
Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H

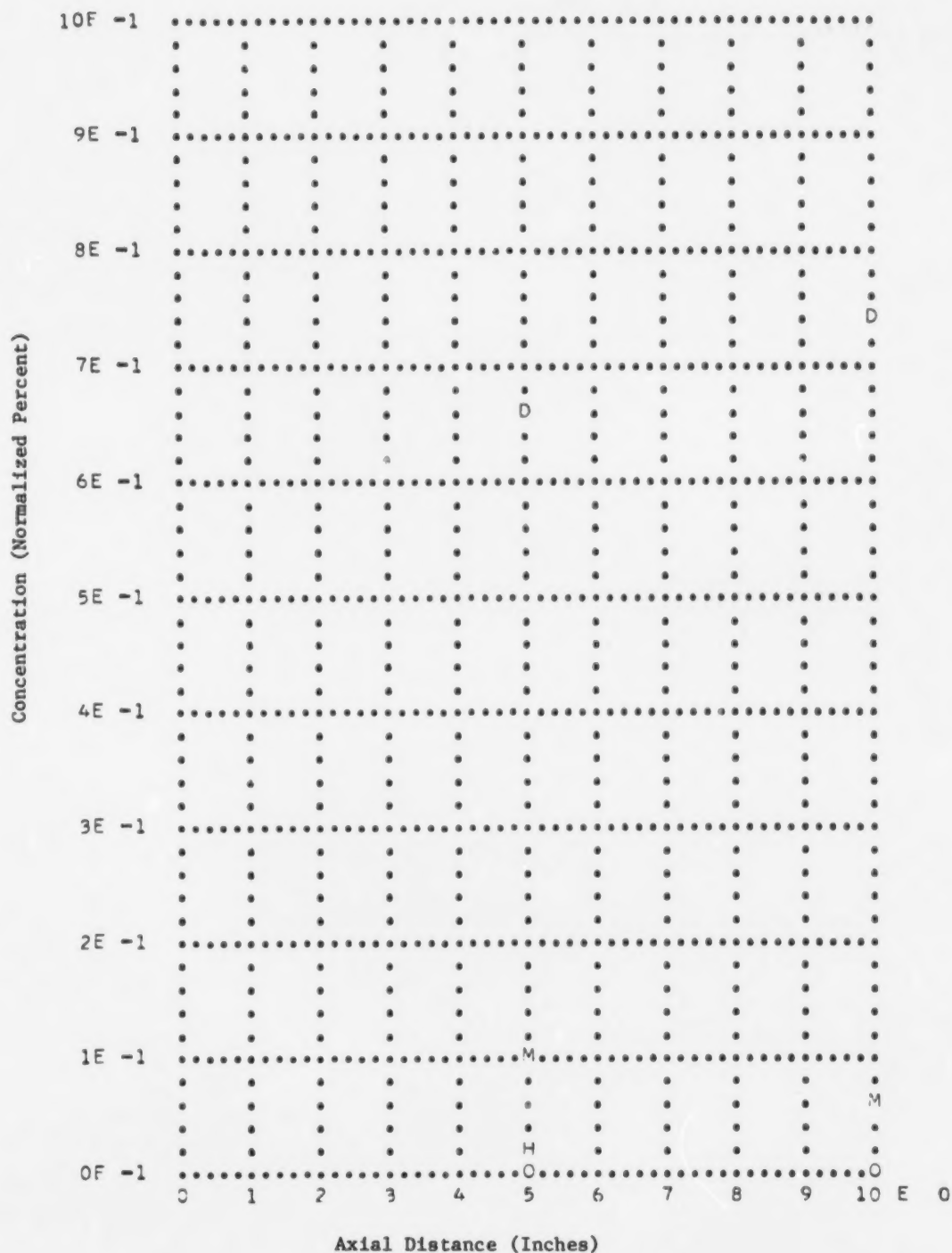


E-6

Run Number 105, Stabilized Diffusion Flame Burner (Turbulent), Methane
Fuel, 101% Stoichiometric Air, Cold Wall

Normalized Species Concentrations CO₂/15, CO/5, O₂/10, HC/5

Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H

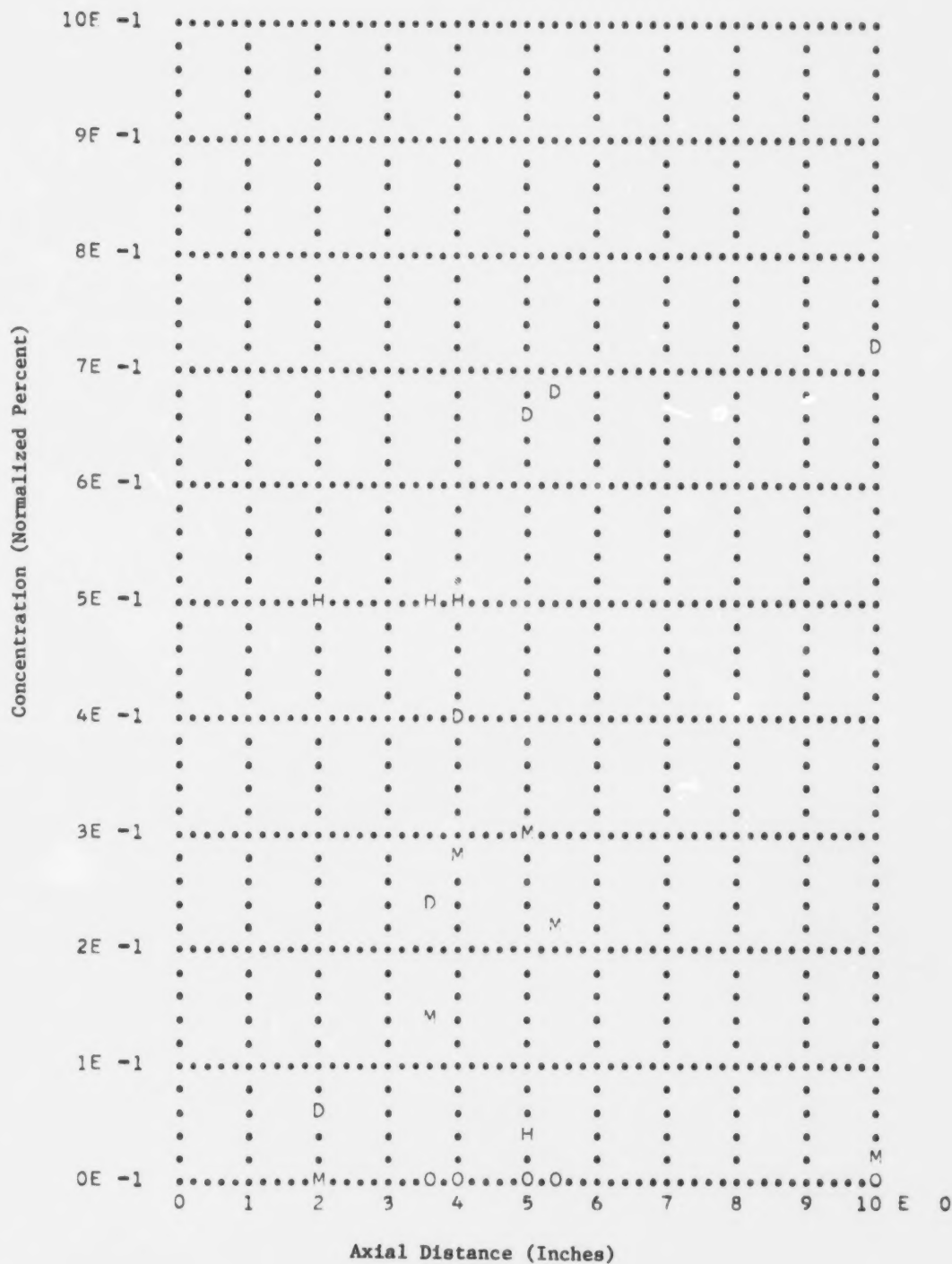


E-7

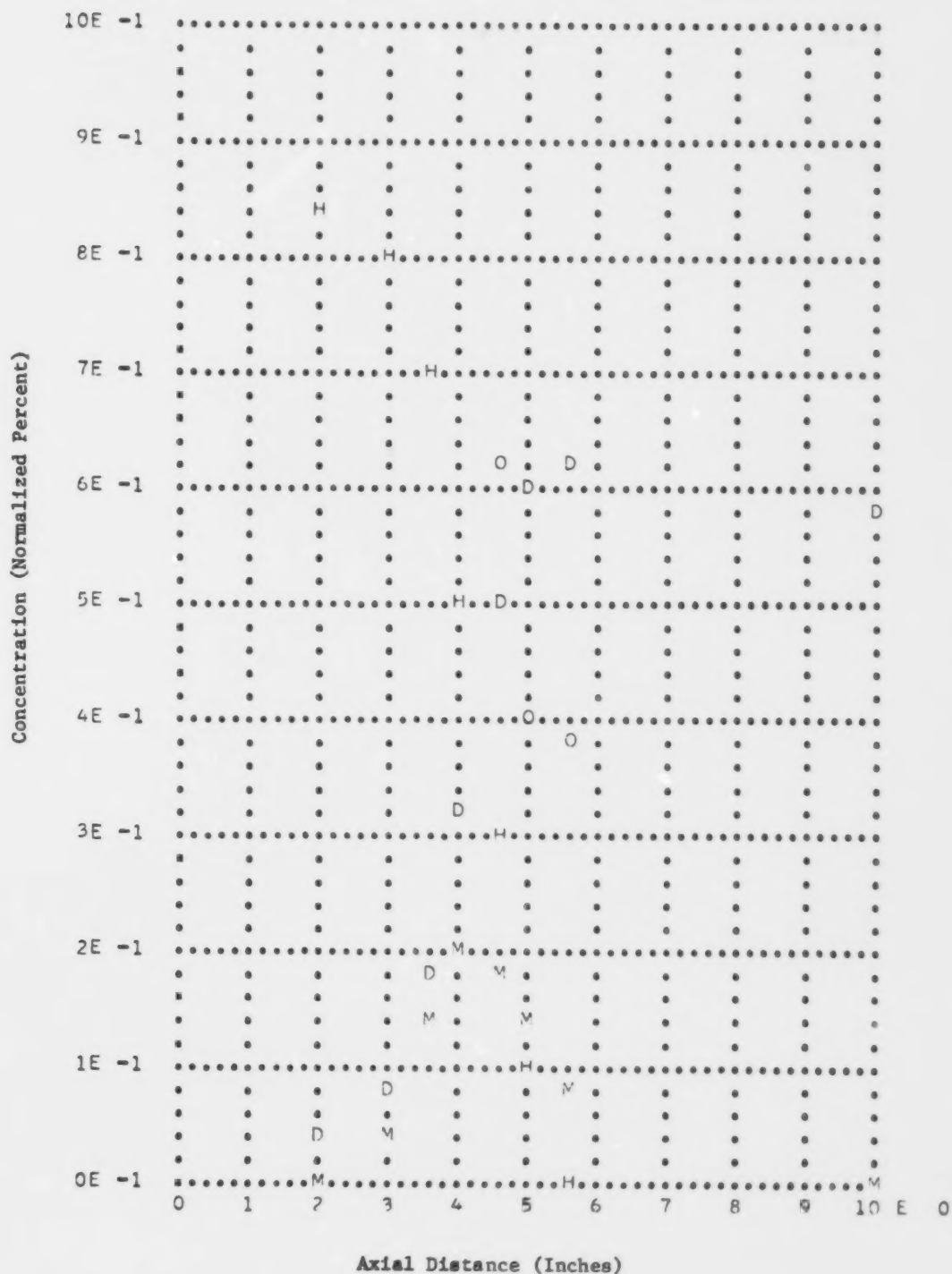
Run Number 106, Stabilized Diffusion Flame Burner (Turbulent), Methane
Fuel, 101% Stoichiometric Air, Cold Wall

Normalized Species Concentrations $\text{CO}_2/15$, $\text{CO}/5$, $\text{O}_2/10$, $\text{HC}/5$

Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



Run Number 108, Stabilized Diffusion Flame Burner (Turbulent), Methane
 Fuel, 120% Stoichiometric Air, Cold Wall
 Normalized Species Concentrations $\text{CO}_2/15$, $\text{CO}/5$, $\text{O}_2/10$, $\text{HC}/5$
 Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H

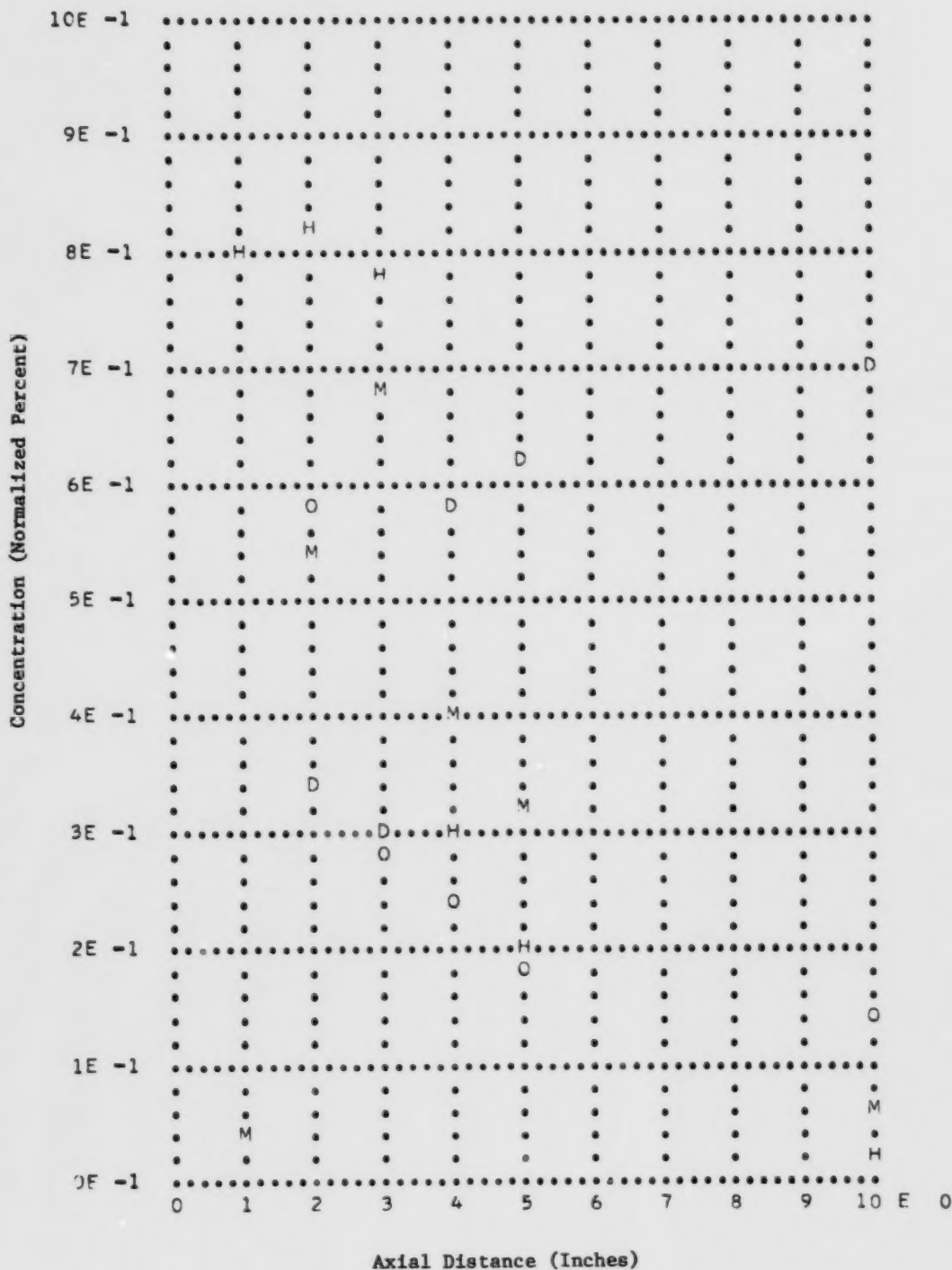


E-9

Run Number 109, Stabilized Diffusion Flame Burner (Laminar), Methane Fuel, 107% Stoichiometric Air, Cold Wall

Normalized Species Concentrations CO₂/15, CO/5, O₂/10, HC/5

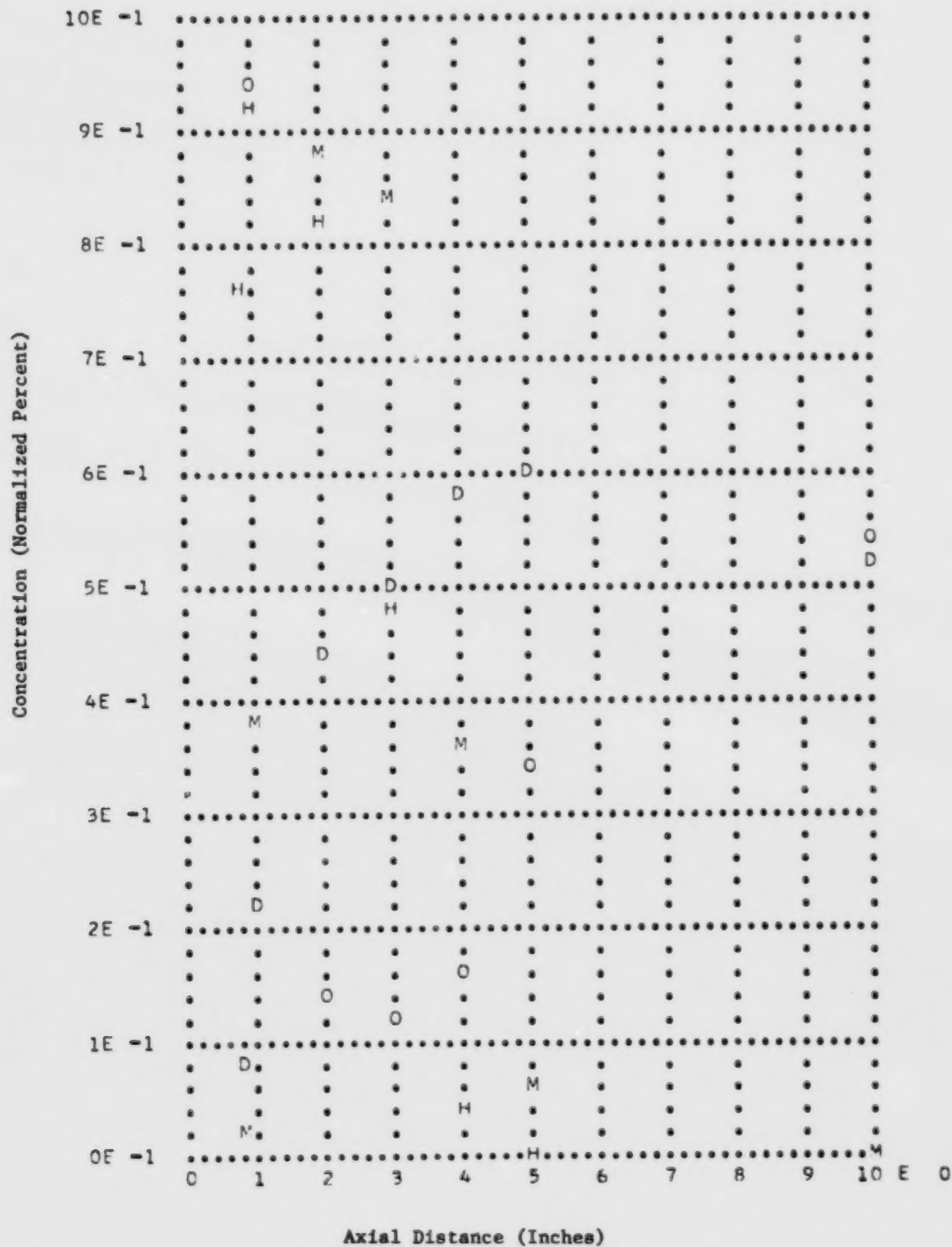
Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



Run Number 109, Stabilized Diffusion Flame Burner (Laminar), Methane
Fuel, 128% Stoichiometric Air, Cold Wall

Normalized Species Concentrations CO₂/15, CO/5, O₂/10, HC/5

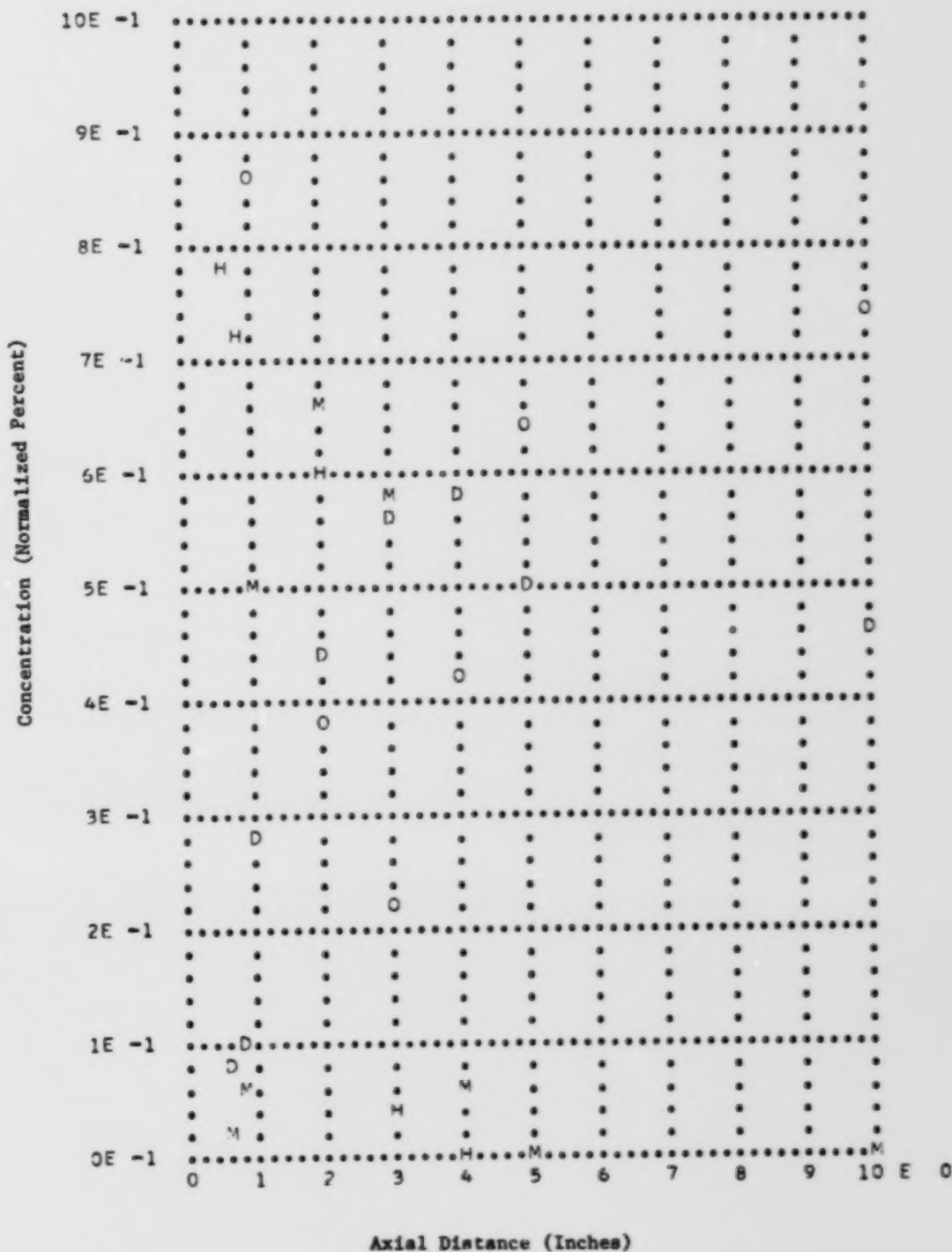
Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



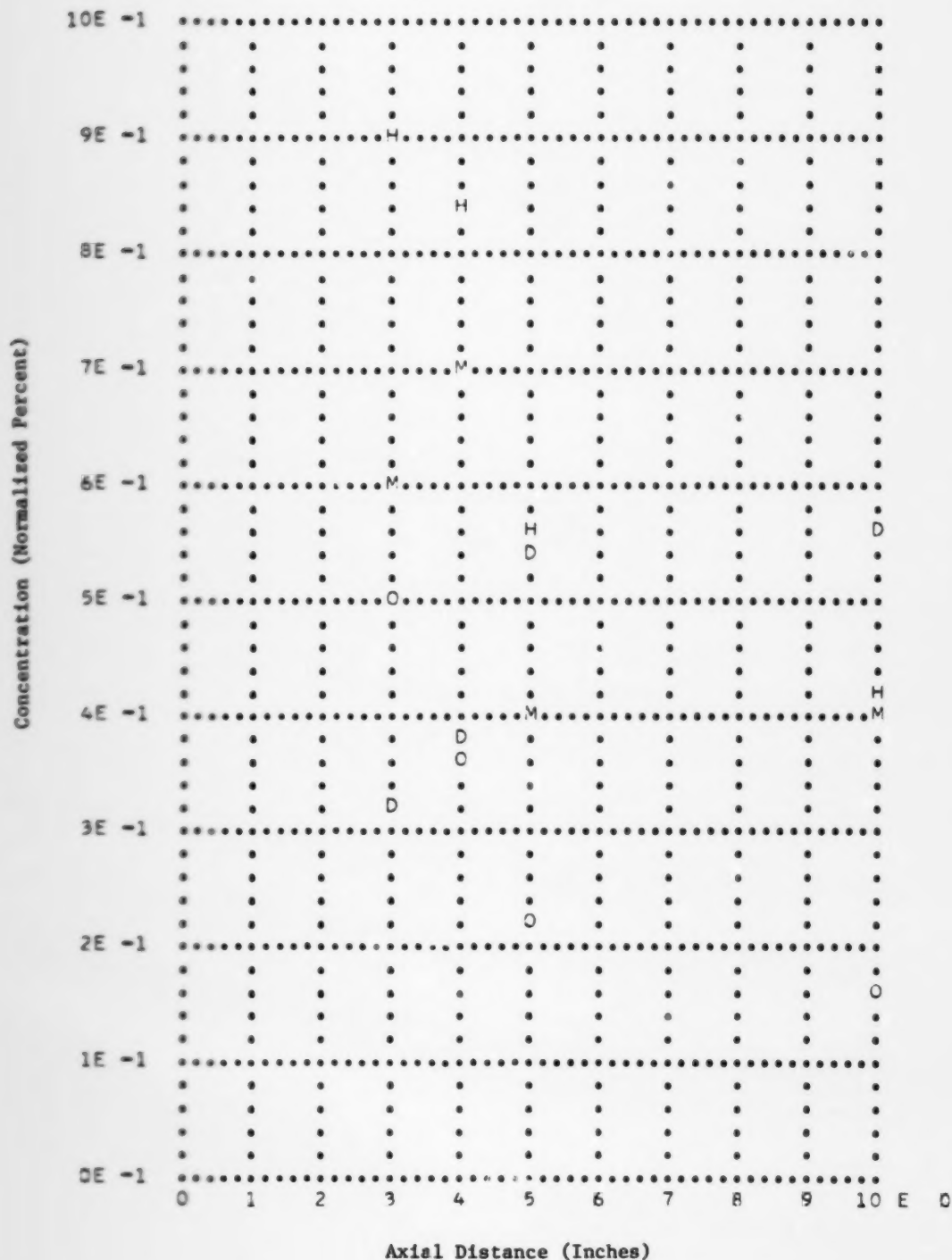
Run Number 110, Stabilized Diffusion Flame Burner (Laminar), Methane
Fuel, 145% Stoichiometric Air, Cold Wall

Normalized Species Concentrations CO₂/15, CO/5, O₂/10, HC/5

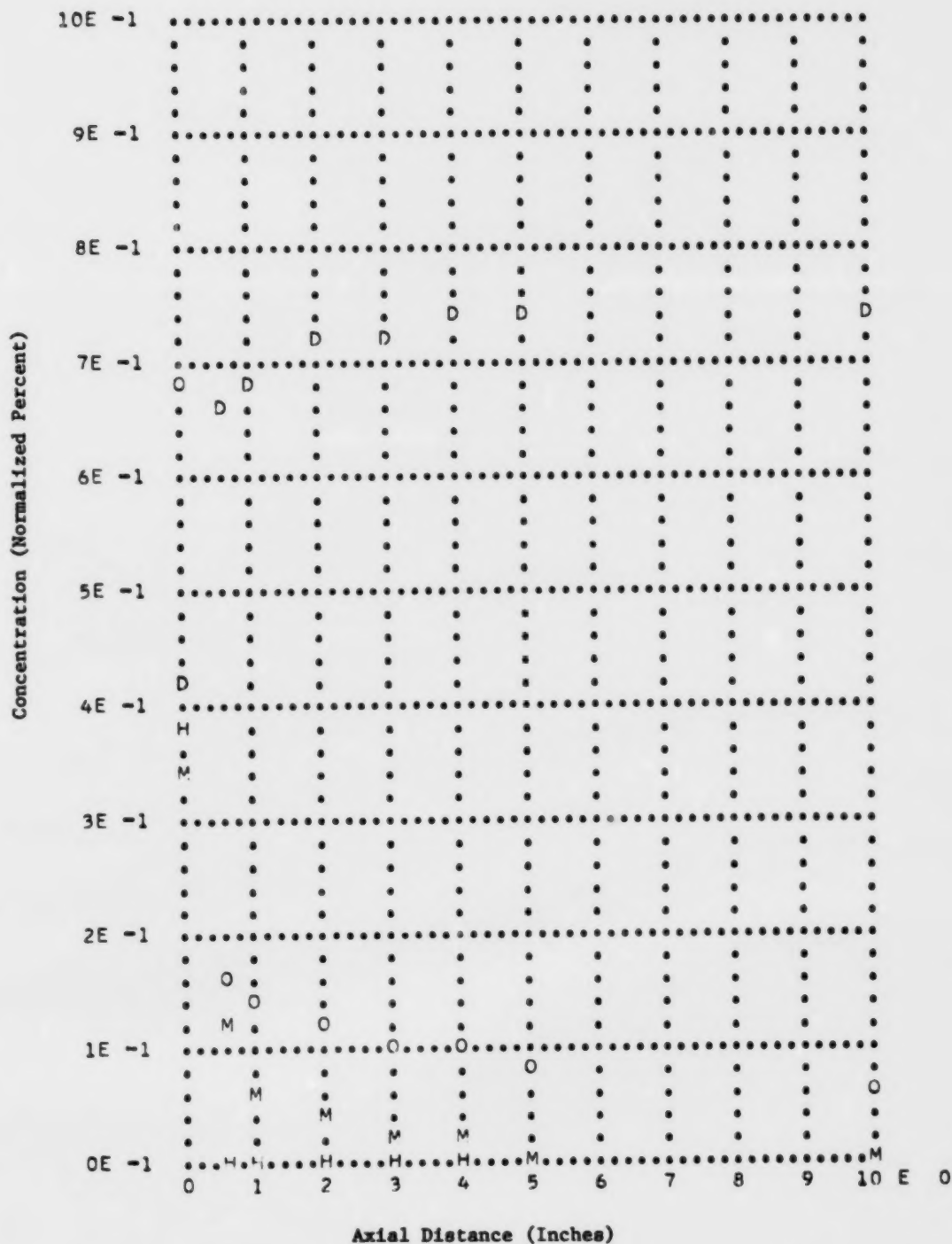
Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



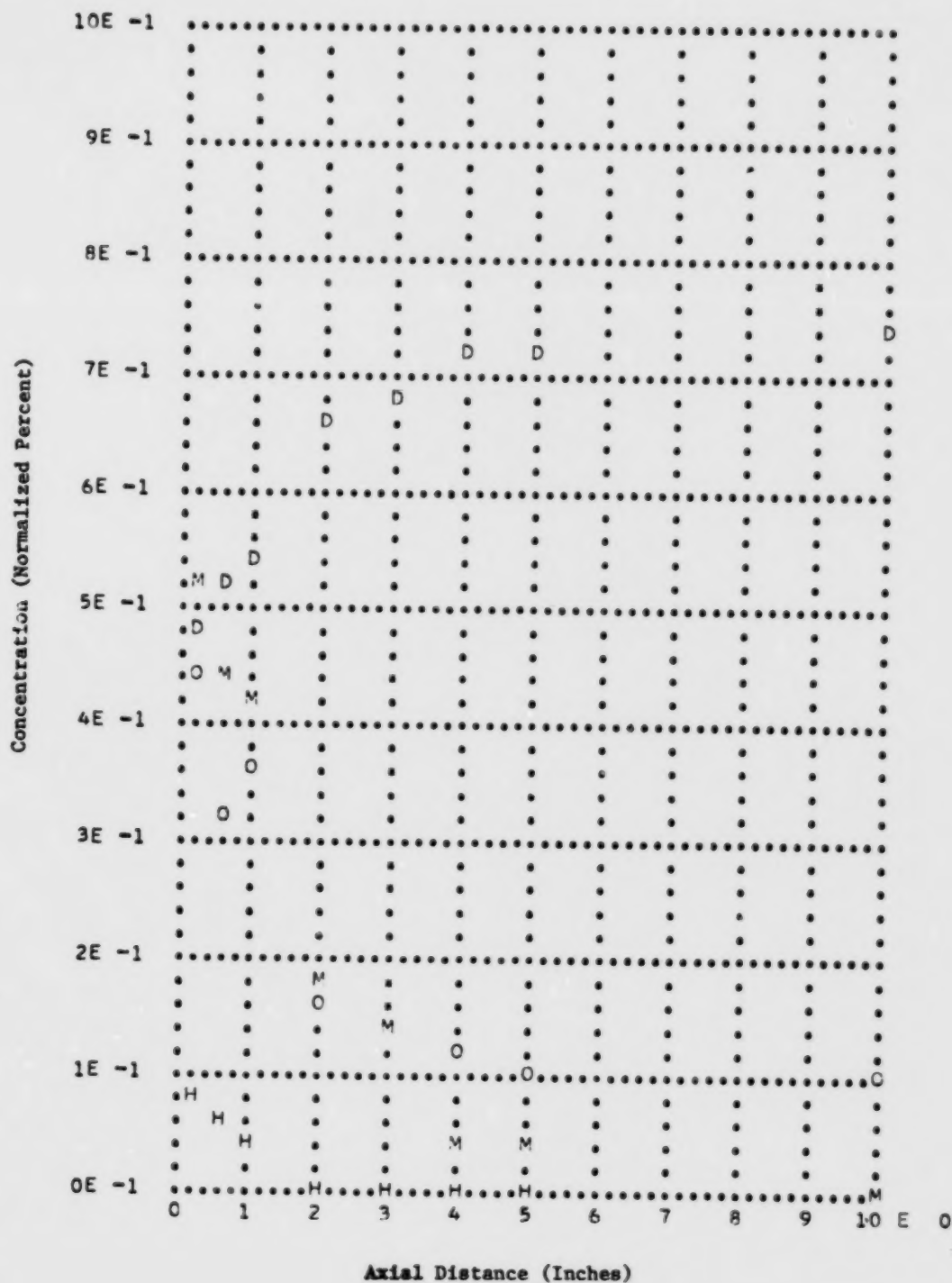
Run Number 110, Stabilized Diffusion Flame Burner (Laminar), Methane
 Fuel, 86% Stoichiometric Air, Cold Wall
 Normalized Species Concentrations $\text{CO}_2/15$, $\text{CO}/5$, $\text{O}_2/10$, $\text{HC}/5$
 Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



Run Number 111, Premixed Flat Flame Burner (Laminar), Methane Fuel,
 104% Stoichiometric Air, Cold Wall
 Normalized Species Concentrations CO₂/15, CO/5, O₂/10, HC/5
 Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



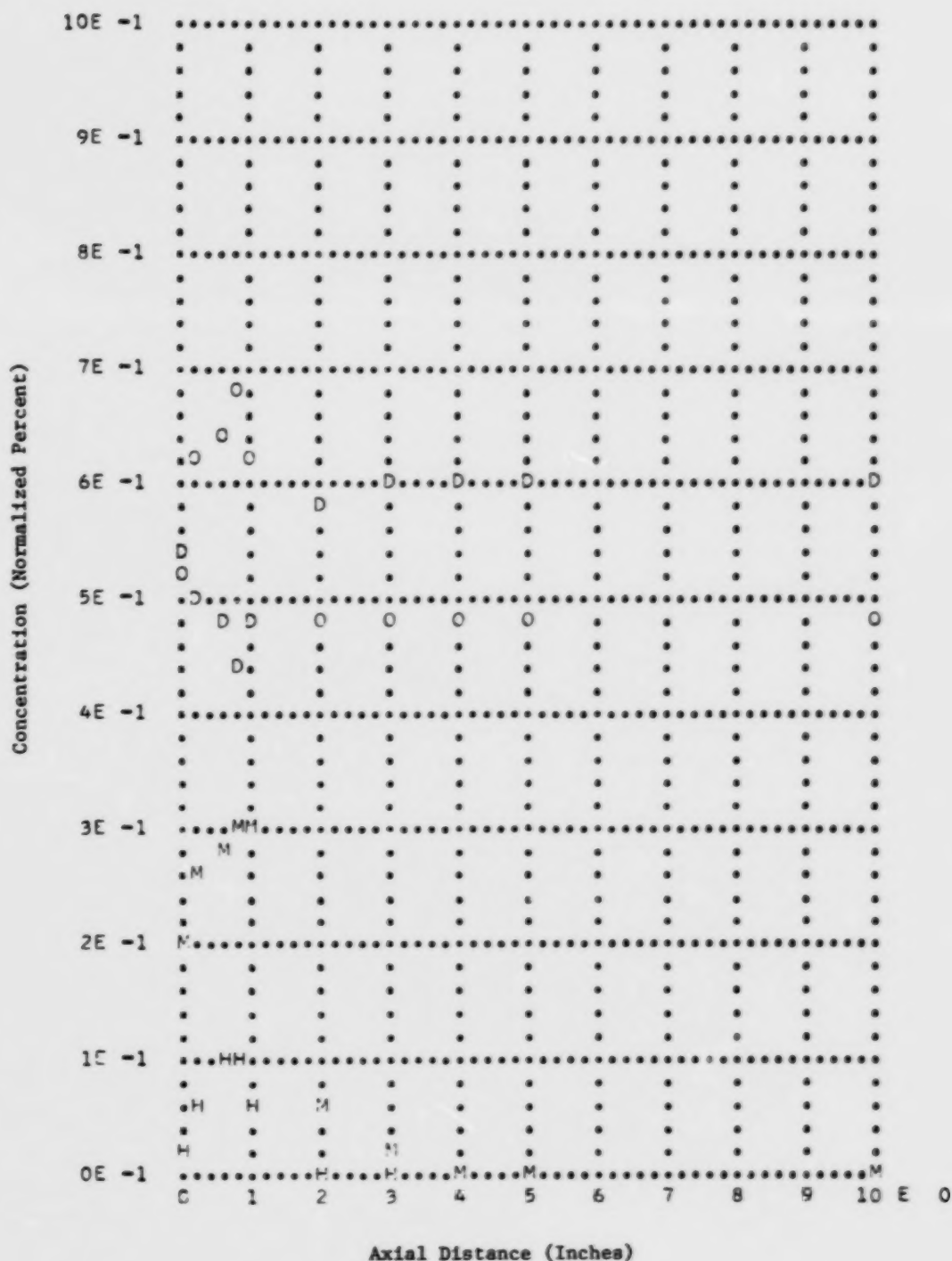
Run Number 112, Premixed Furnace Burner (Turbulent), Methane Fuel,
 96% Stoichiometric Air, Cold Wall
 Normalized Species Concentrations $\text{CO}_2/15$, $\text{CO}/5$, $\text{O}_2/10$, $\text{HC}/5$
 Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



Run Number 113, Premixed Furnace Burner (Turbulent), Methane Fuel
 115% Stoichiometric Air, Cold Wall

Normalized Species Concentrations CO₂/15, CO/5, O₂/10, HC/5

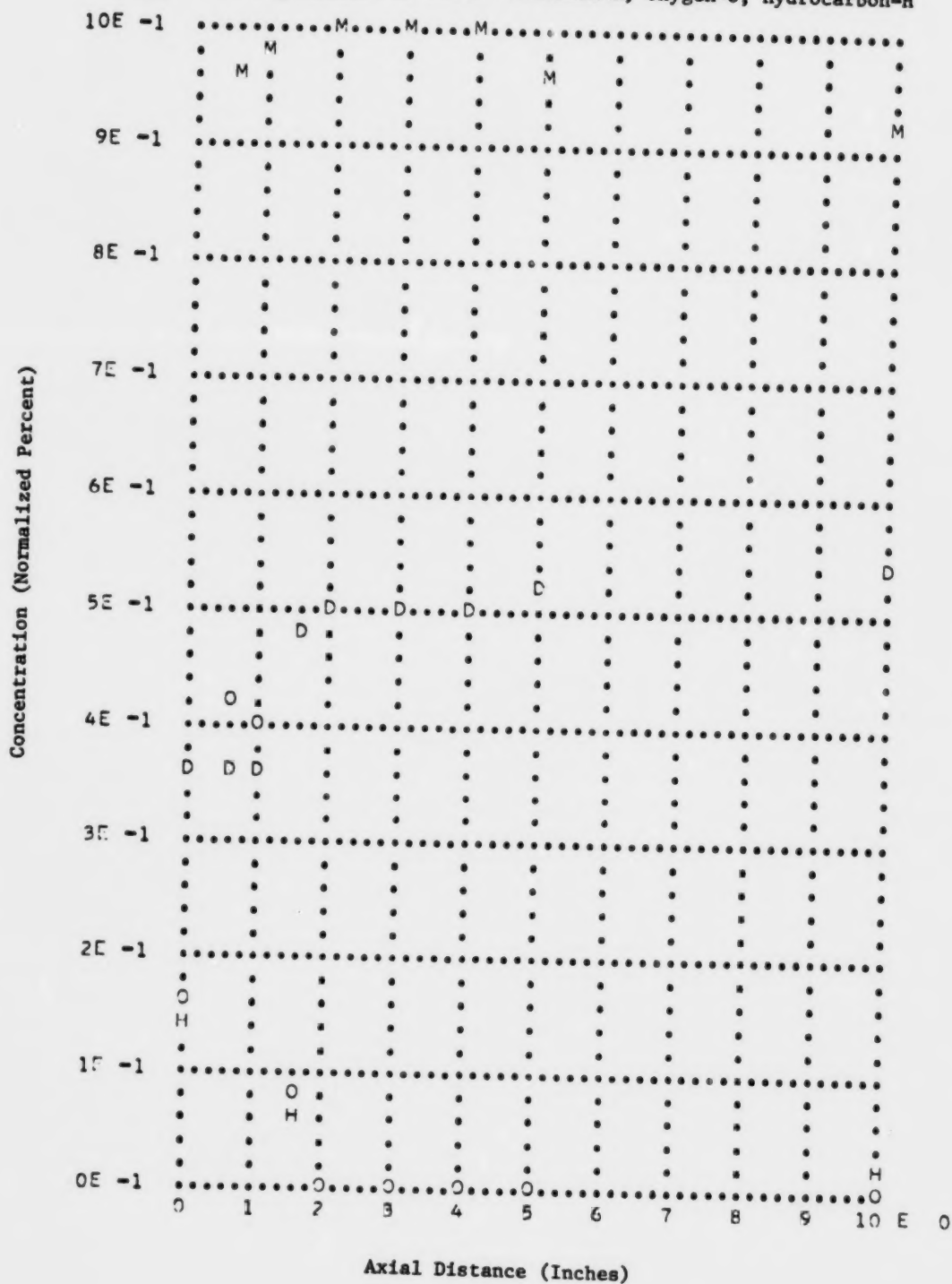
Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



Run Number 114, Premixed Furnace Burner (Turbulent), Methane Fuel,
76% Stoichiometric Air, Cold Wall

Normalized Species Concentrations $\text{CO}_2/15$, $\text{CO}/5$, $\text{O}_2/10$, $\text{HC}/5$

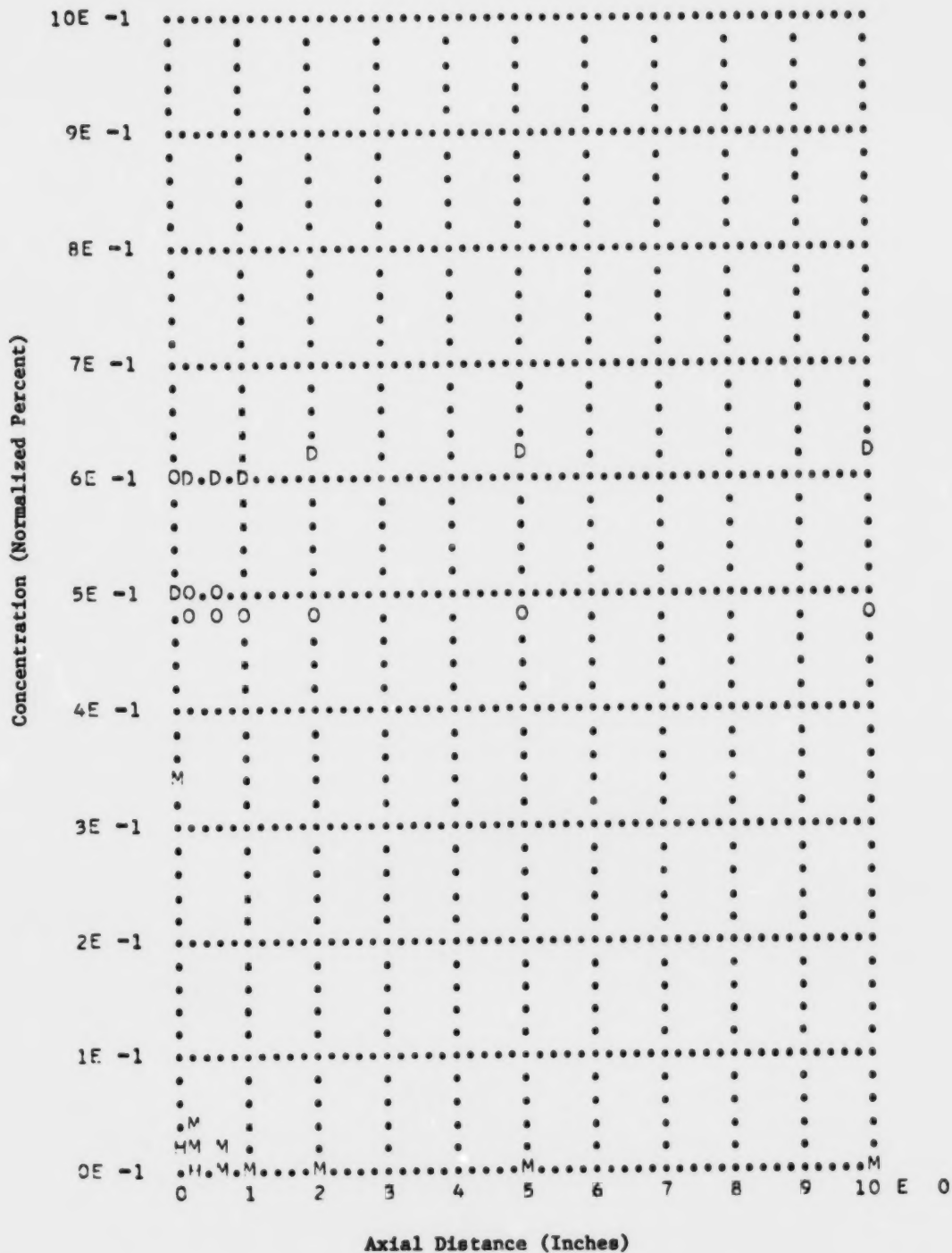
Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



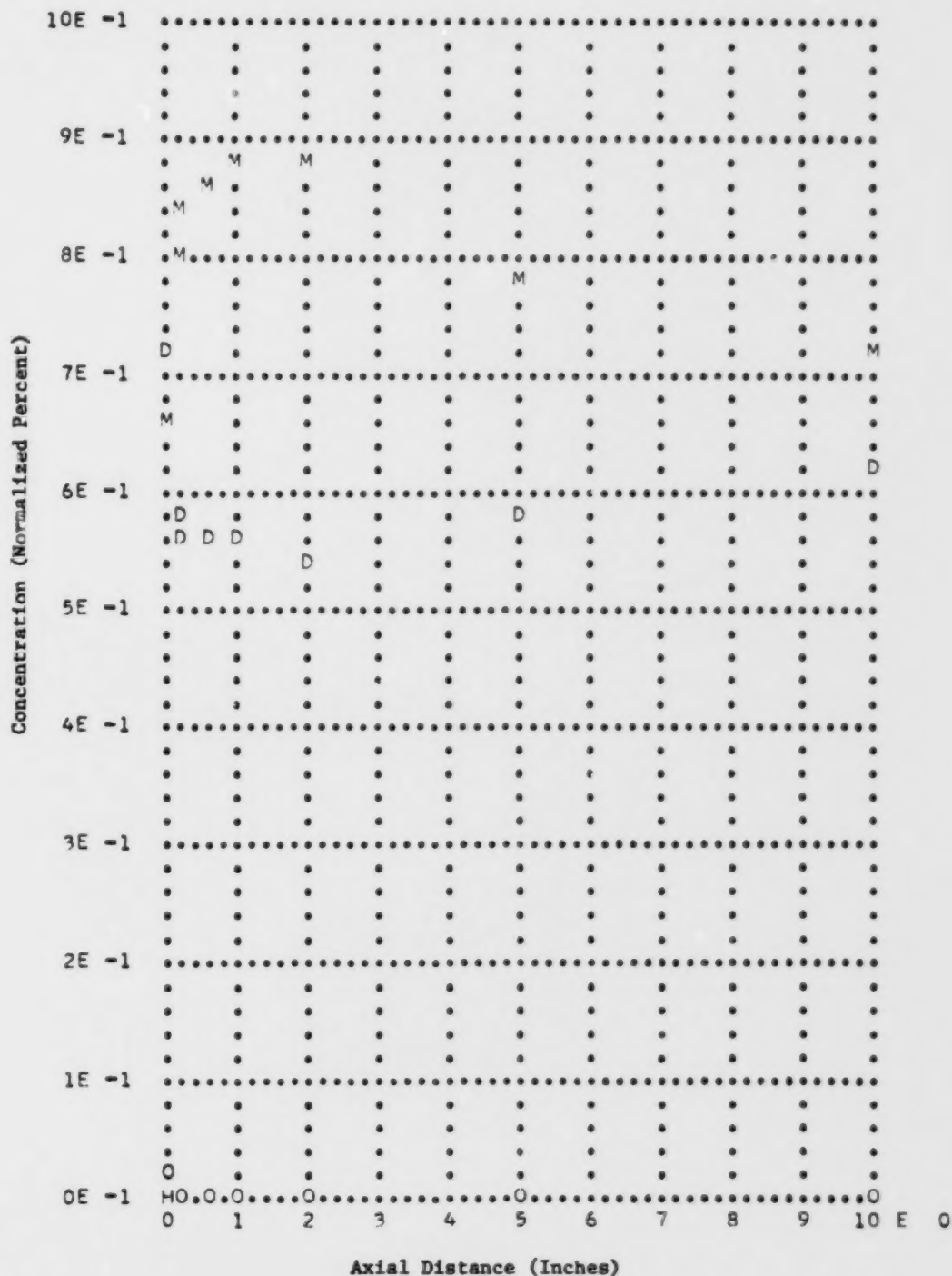
Run Number 116, Premixed Flat Flame Burner (Laminar), Methane Fuel,
119% Stoichiometric Air, Cold Wall

Normalized Species Concentrations CO₂/15, CO/5, O₂/10, HC/5

Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



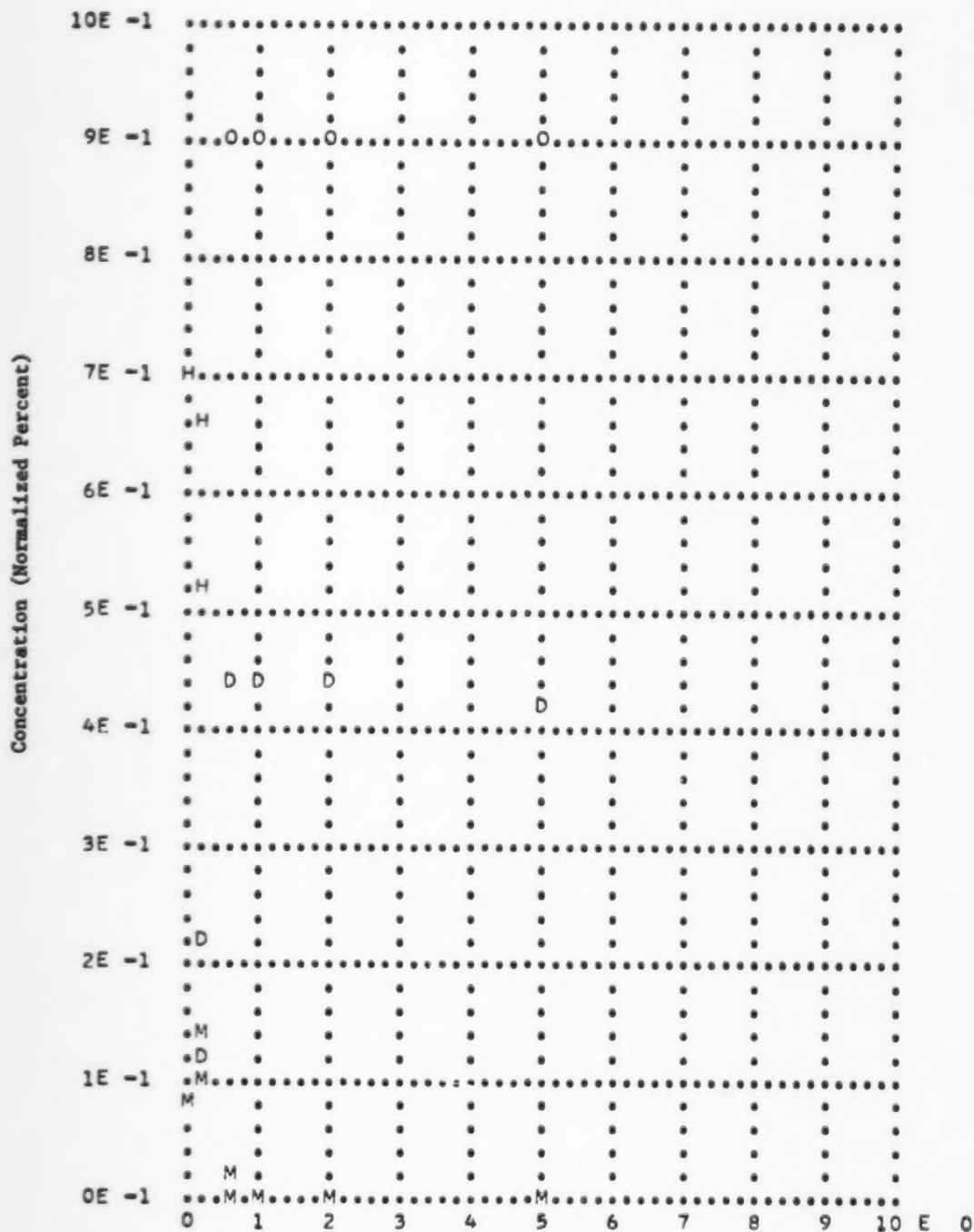
Run Number 116, Premixed Flat Flame Burner (Laminar), Methane Fuel,
 80% Stoichiometric Air, Cold Wall
 Normalized Species Concentrations $\text{CO}_2/15$, $\text{CO}/5$, $\text{O}_2/10$, $\text{HC}/5$
 Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



Run Number 117, Premixed Flat Flame Burner (Laminar), Methane Fuel,
161% Stoichiometric Air, Hot Wall 1430C

Normalized Species Concentrations CO₂/15, CO/5, O₂/10, HC/5

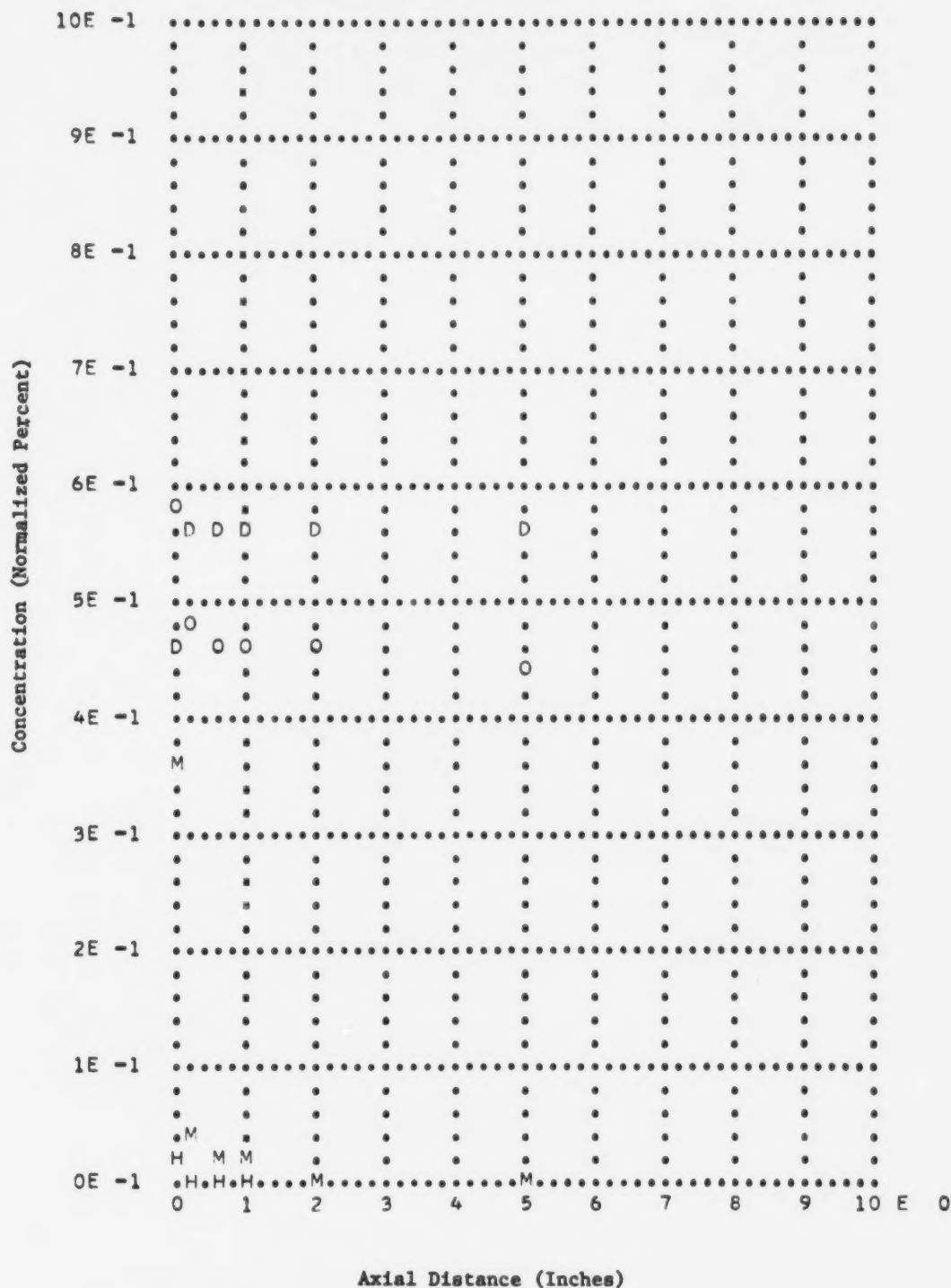
Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



Run Number 117, Premixed Flat Flame Burner (Laminar), Methane Fuel,
119% Stoichiometric Air, Hot Wall 1430C

Normalized Species Concentrations $\text{CO}_2/15$, $\text{CO}/5$, $\text{O}_2/10$, $\text{HC}/5$

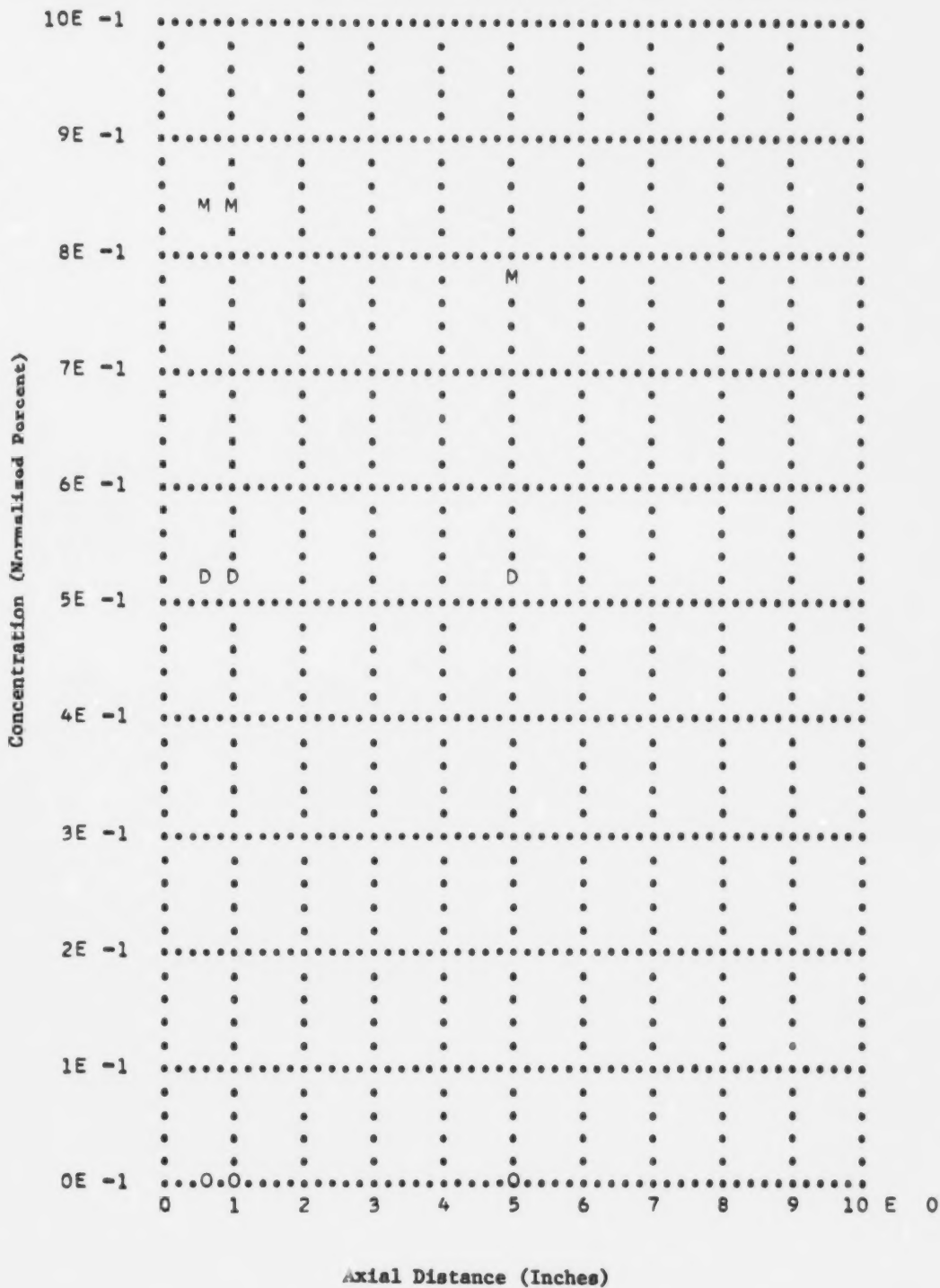
Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



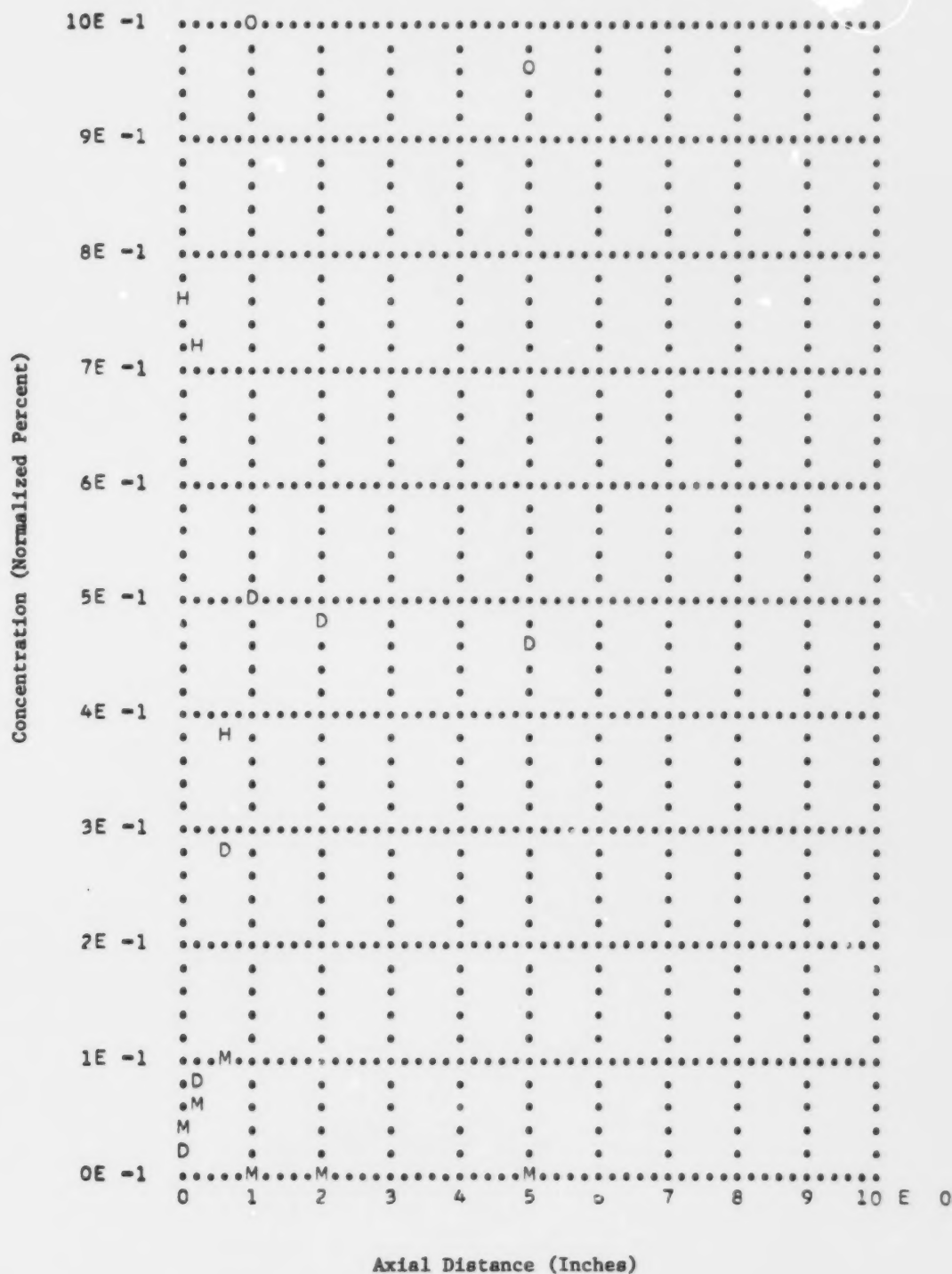
Run Number 117, Premixed Flat Flame Burner (Laminar), Methane Fuel,
80% Stoichiometric Air, Hot Wall 1825C

Normalized Species Concentrations CO₂/15, CO/5, O₂/10, HC/5

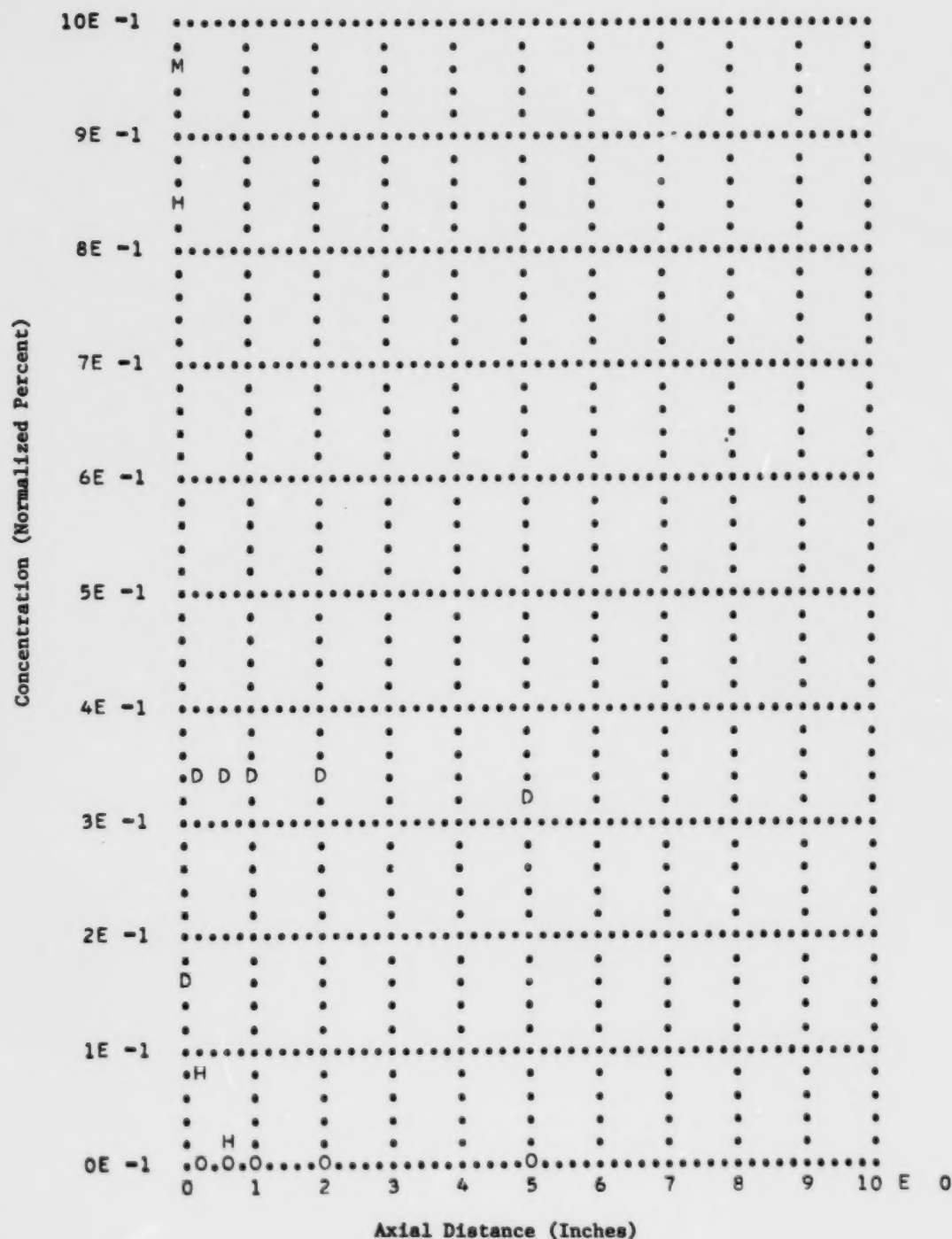
Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=■



Run Number 118, Premixed Flat Flame Burner (Laminar), Propane Fuel,
 161% Stoichiometric Air, Hot Wall 1450C
 Normalized Species Concentrations $\text{CO}_2/15$, $\text{CO}/5$, $\text{O}_2/10$, $\text{HC}/5$
 Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



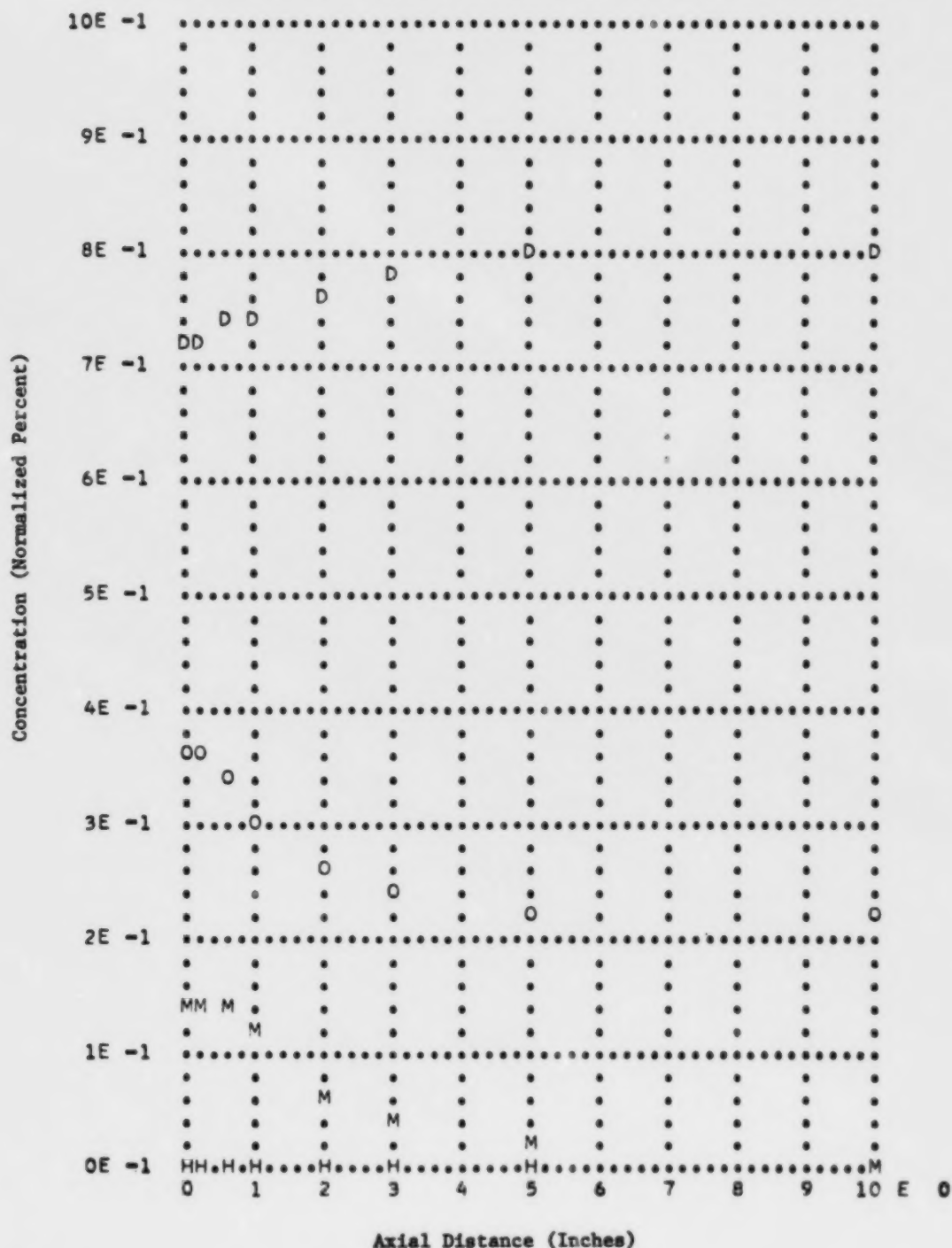
Run Number 118, Premixed Flat Flame Burner (Laminar), Propane Fuel,
 61% Stoichiometric Air, Hot Wall 1565C
 Normalized Species Concentrations $\text{CO}_2/15$, $\text{CO}/5$, $\text{O}_2/10$, $\text{HC}/5$
 Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



Run Number 119, Premixed Flat Flame Burner (Turbulent), Propane Fuel,
110% Stoichiometric Air, Cold Wall

Normalized Species Concentrations $\text{CO}_2/15$, $\text{CO}/5$, $\text{O}_2/10$, $\text{HC}/5$

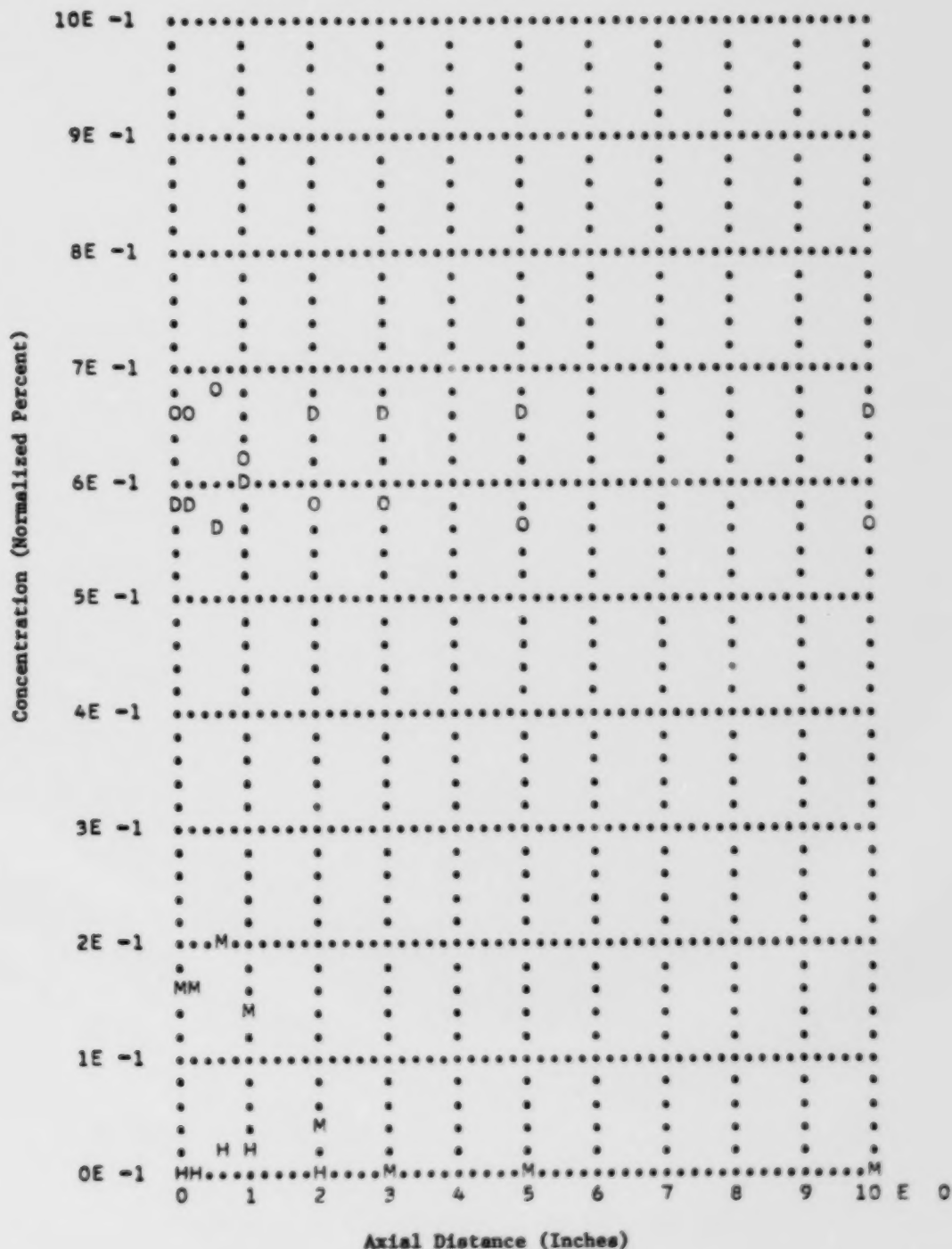
Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



Run Number 119, Premixed Flat Flame Burner (Turbulent), Propane Fuel,
132% Stoichiometric Air, Cold Wall

Normalized Species Concentrations $\text{CO}_2/15$, $\text{CO}/5$, $\text{O}_2/10$, $\text{HC}/5$

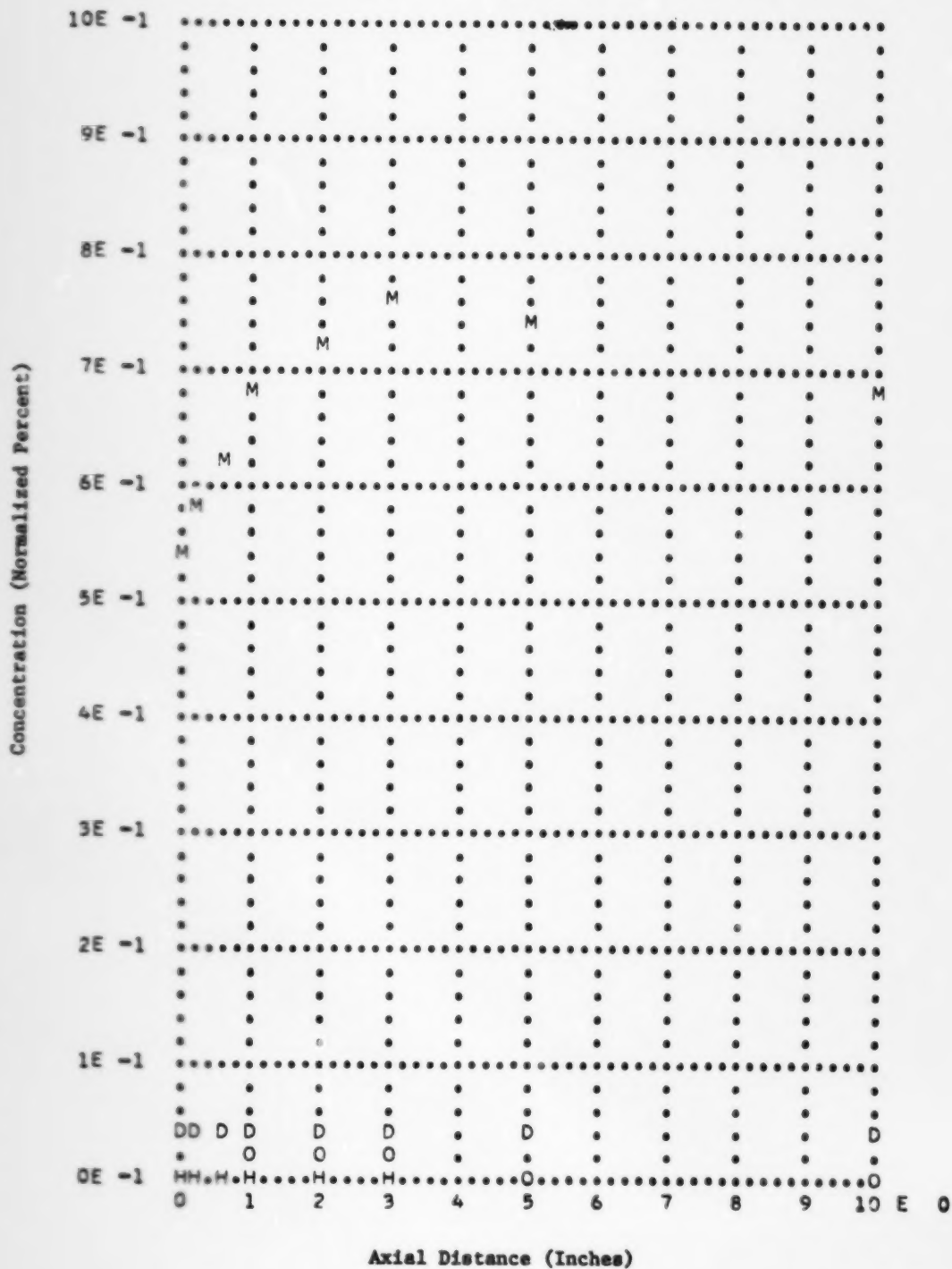
Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



Run Number 119, Premixed Flat Flame Burner (Turbulent), Propane Fuel,
88% Stoichiometric Air, Cold Wall

Normalized Species Concentrations $\text{CO}_2/15$, $\text{CO}/5$, $\text{O}_2/10$, $\text{HC}/5$

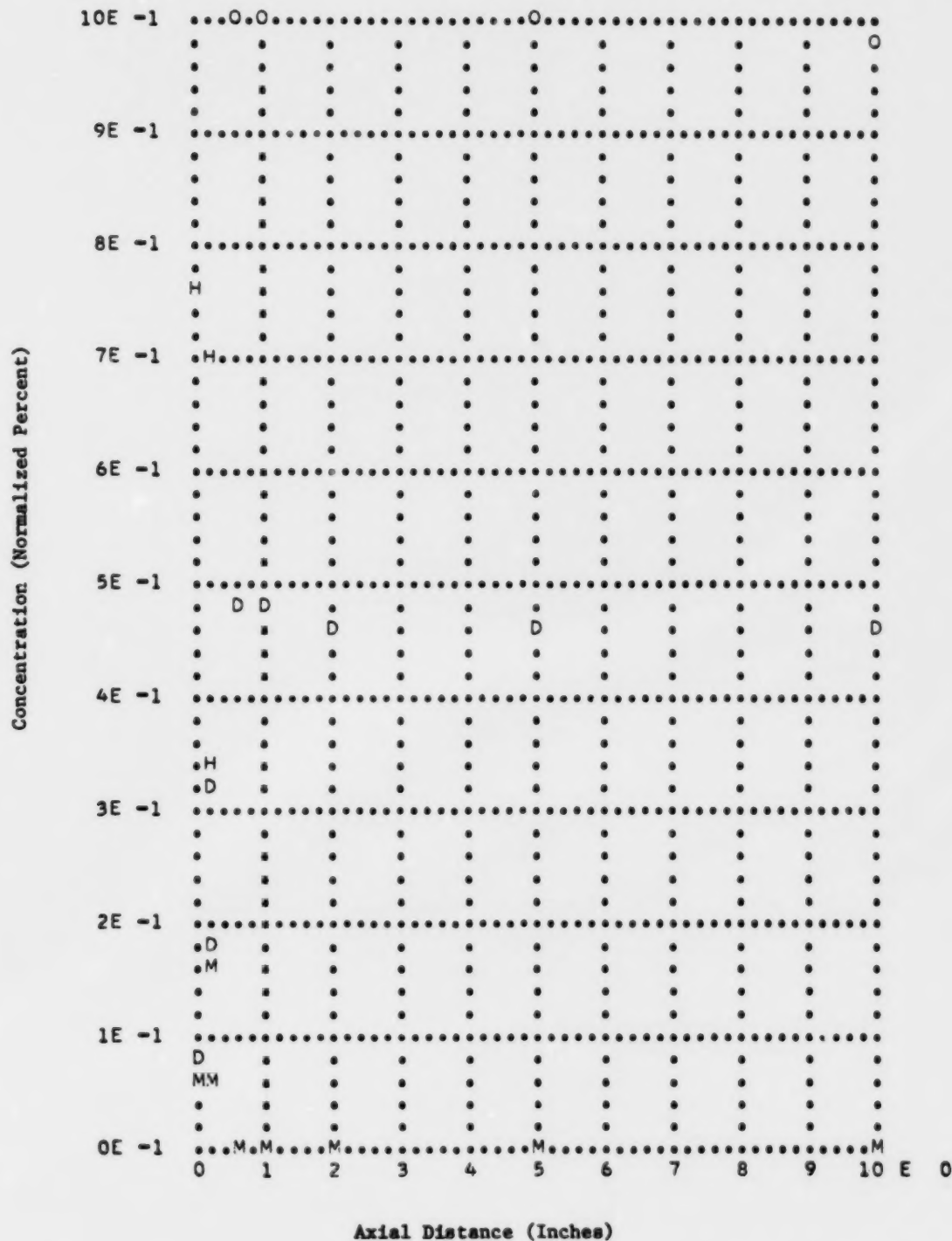
Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



Run Number 120, Premixed Furnace Burner (Laminar), Propane Fuel,
156% Stoichiometric Air, Hot Wall 1495C

Normalized Species Concentrations CO₂/15, CO/5, O₂/10, HC/5

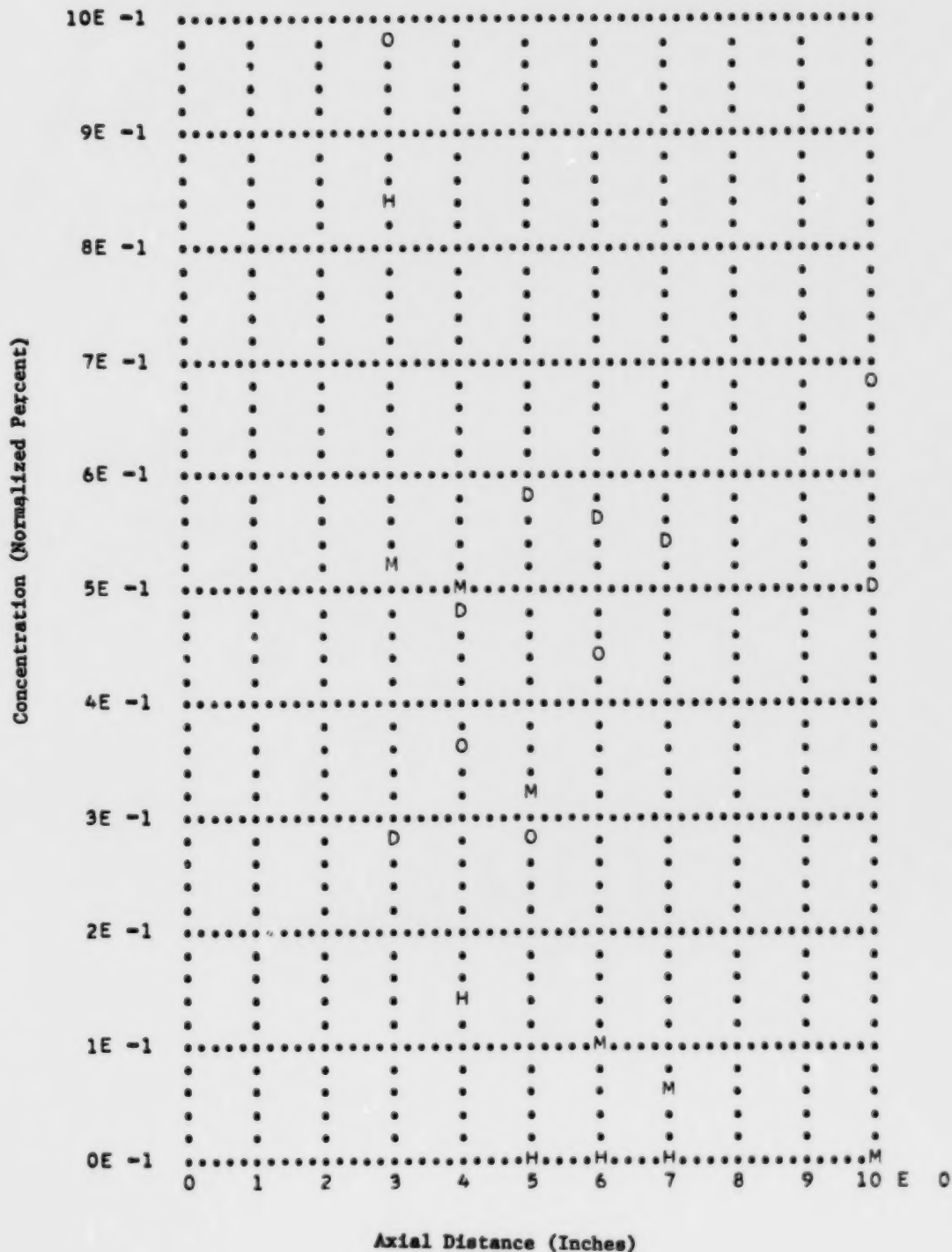
Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



Run Number 122, Stabilized Diffusion Flame Burner (Turbulent), Methane Fuel, 160% Stoichiometric Air, Hot Wall 1450C

Normalized Species Concentrations CO₂/15, CO/5, O₂/10, HC/5

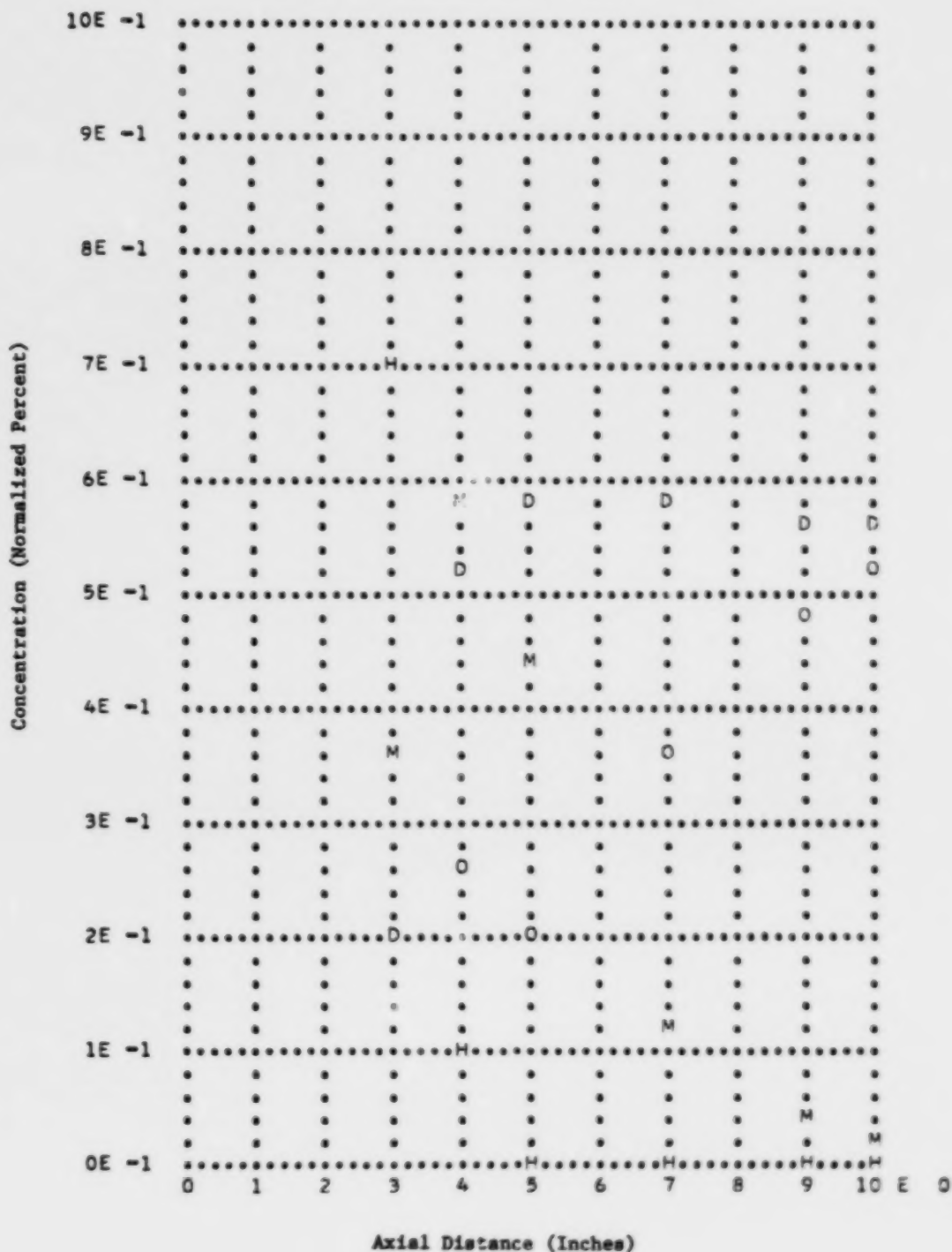
Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



Run Number 123, Stabilized Diffusion Flame Burner (Turbulent), Methane
Fuel, 140% Stoichiometric Air, Hot Wall 1590C

Normalized Species Concentrations $CO_2/15$, $CO/5$, $O_2/10$, $HC/5$

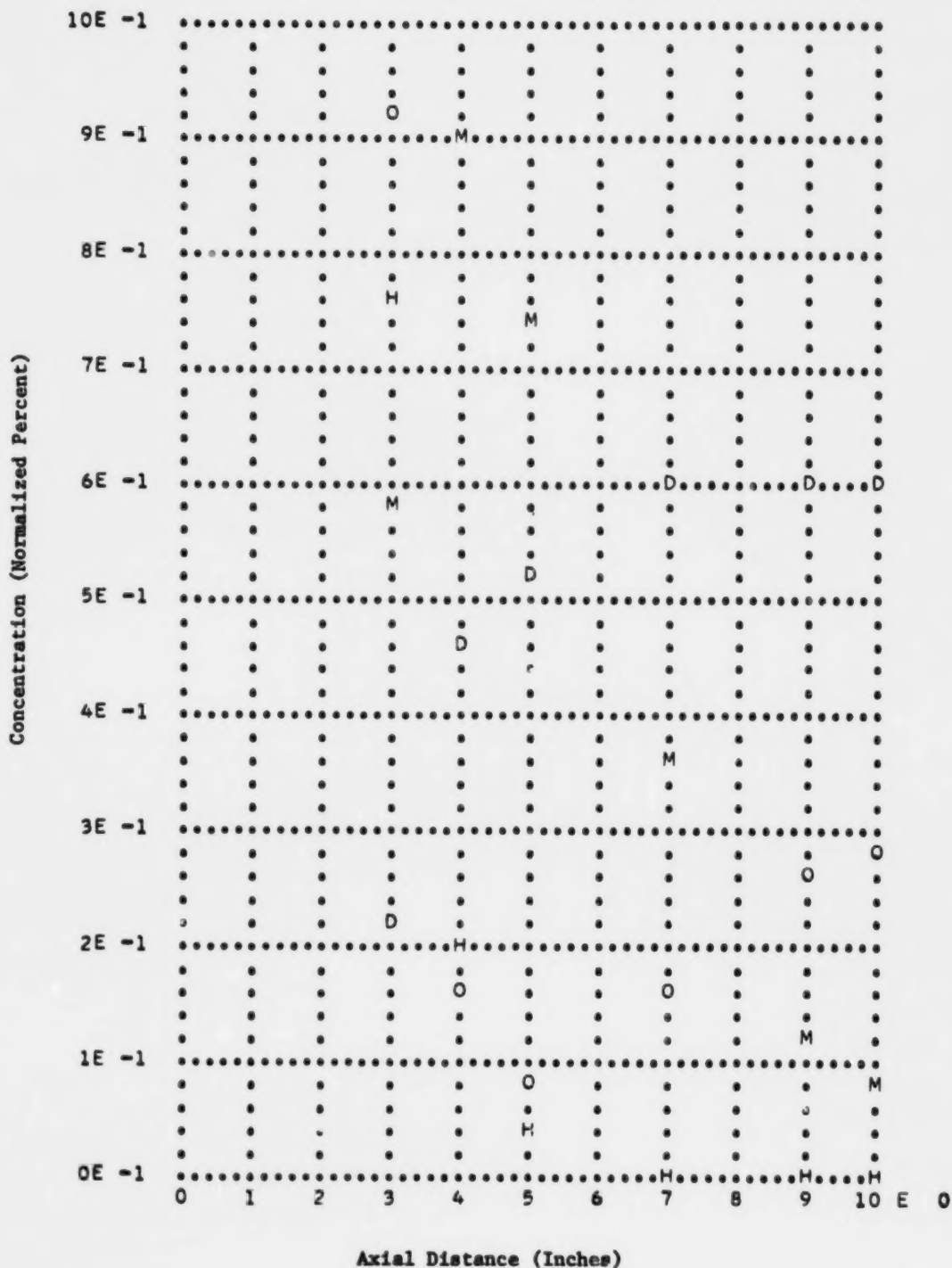
Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



Run Number 123, Stabilized Diffusion Flame Burner (Turbulent), Methane
Fuel, 120% Stoichiometric Air, Hot Wall 1775C

Normalized Species Concentrations $\text{CO}_2/15$, $\text{CO}/5$, $\text{O}_2/10$, $\text{HC}/5$

Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H

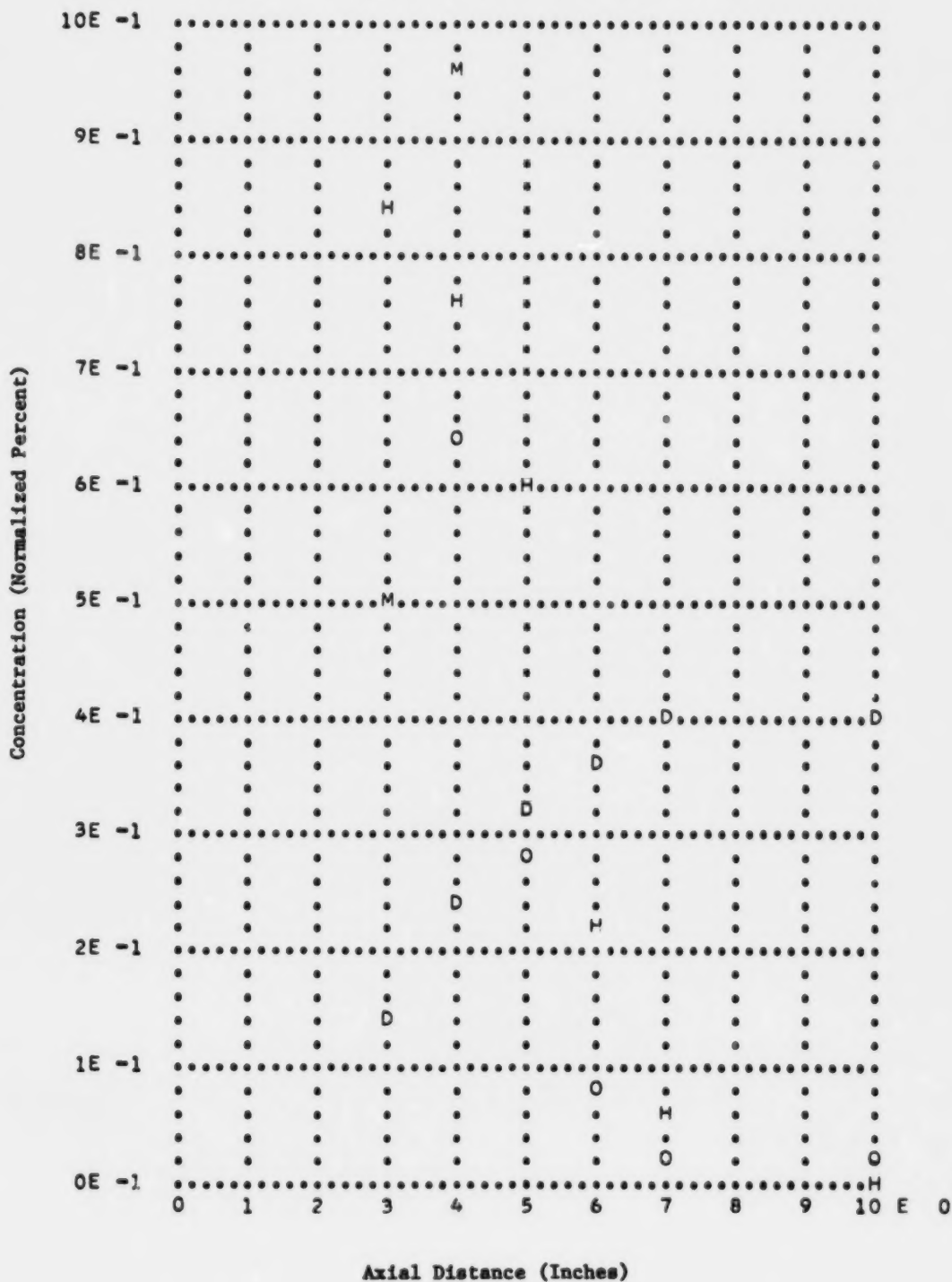


E-31

Run Number 123, Stabilized Diffusion Flame Burner (Turbulent), Methane
Fuel, 80% Stoichiometric Air, Hot Wall 1825C

Normalized Species Concentrations CO₂/15, CO/5, O₂/10, HC/5

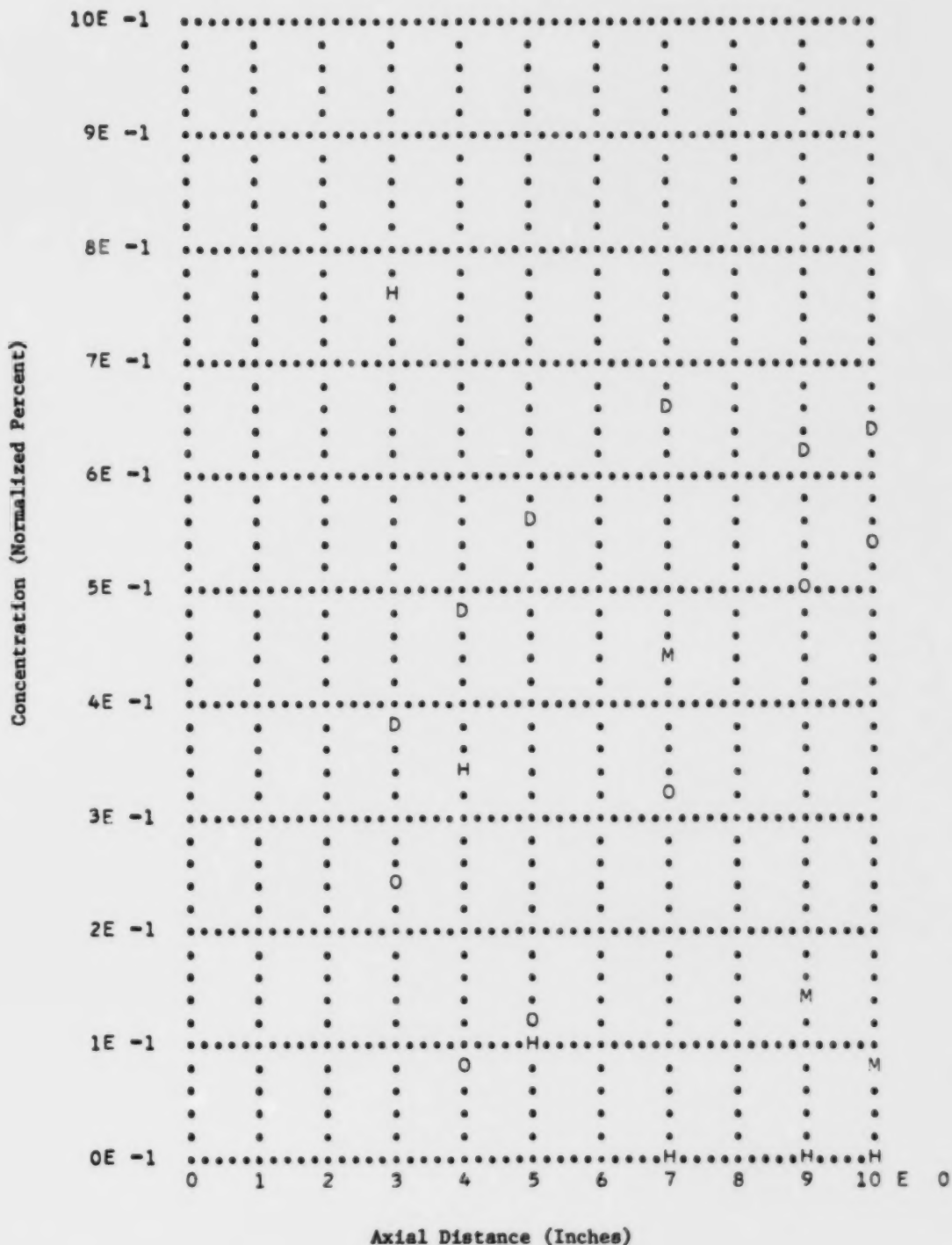
Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



Run Number 125, Stabilized Diffusion Flame Burner (Turbulent), Propane
Fuel, 160% Stoichiometric Air, Hot Wall 1425C

Normalized Species Concentrations $\text{CO}_2/15$, $\text{CO}/5$, $\text{O}_2/10$, $\text{HC}/5$

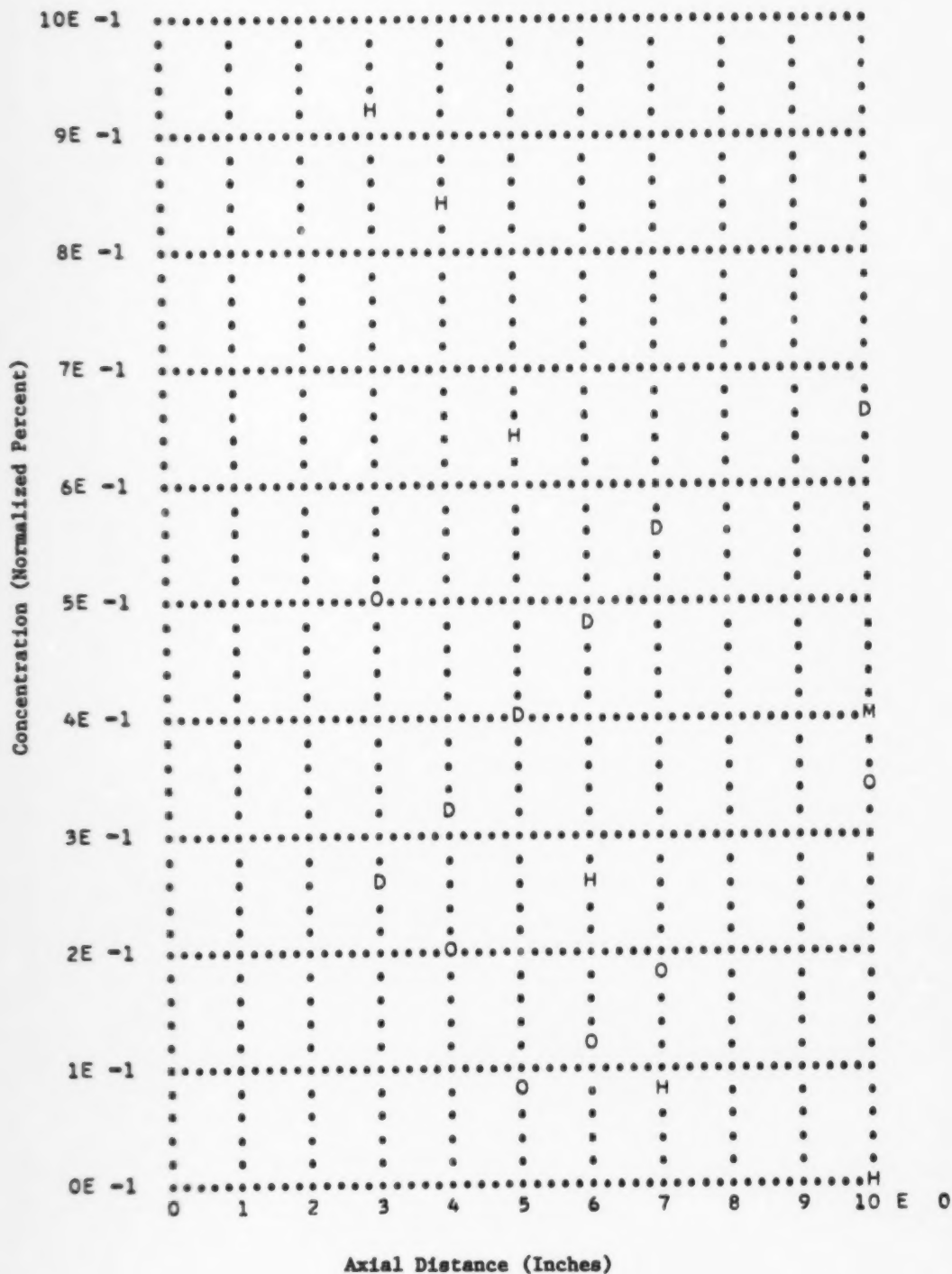
Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



Run Number 126, Stabilized Diffusion Flame Burner (Turbulent), Propane
Fuel, 141% Stoichiometric Air, Hot Wall 1610C

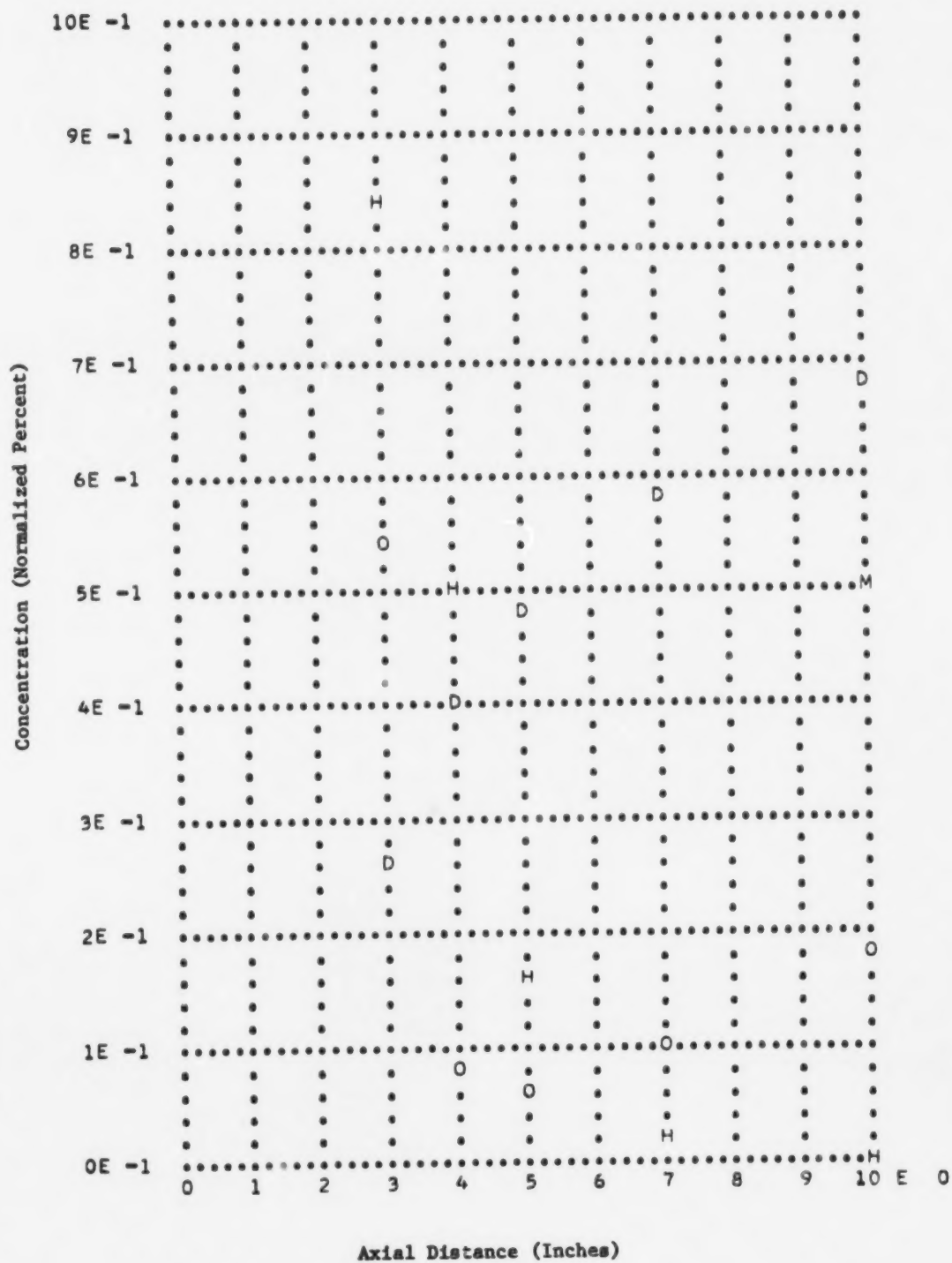
Normalized Species Concentrations CO₂/15, CO/5, O₂/10, HC/5

Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



Run Number 127, Stabilized Diffusion Flame Burner (Turbulent), Propane Fuel, 114% Stoichiometric Air, Hot Wall 1870C

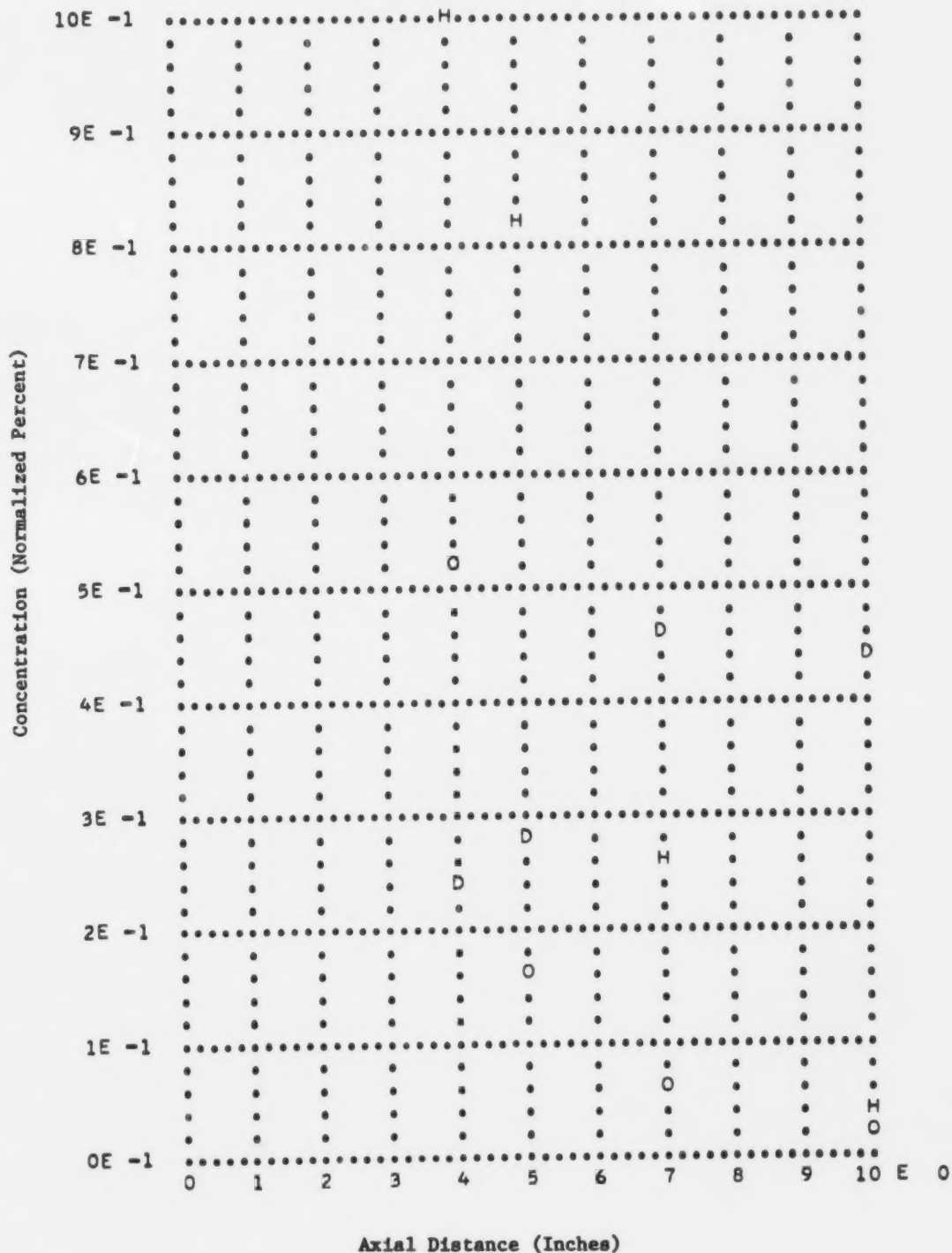
Normalized Species Concentrations $\text{CO}_2/15$, $\text{CO}/5$, $\text{O}_2/10$, $\text{HC}/5$
 Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



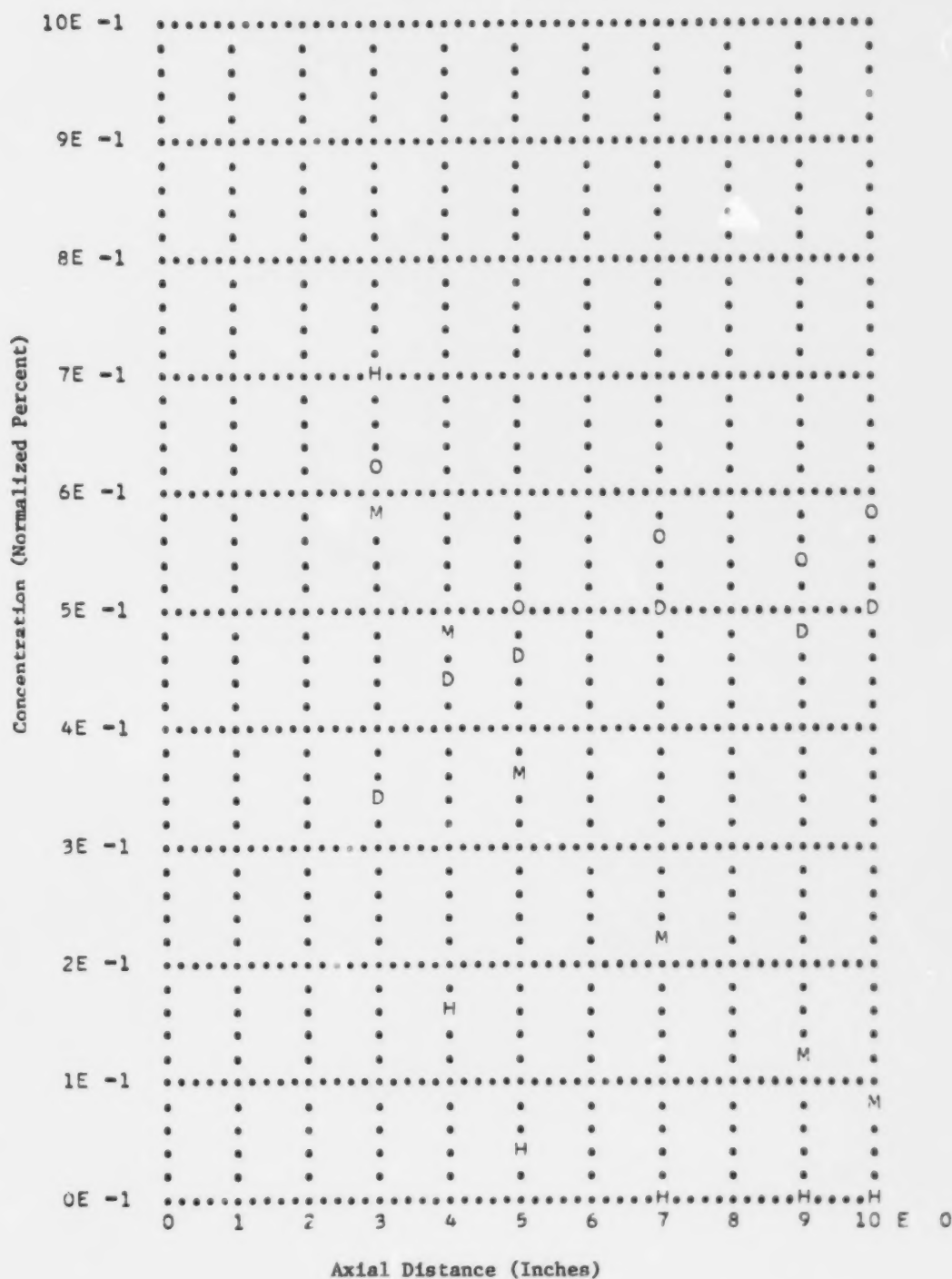
Run Number 127, Stabilized Diffusion Flame Burner (Turbulent), Propane
Fuel, 80% Stoichiometric Air, Hot Wall 1870C

Normalized Species Concentrations $\text{CO}_2/15$, $\text{CO}/5$, $\text{O}_2/10$, $\text{HC}/5$

Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



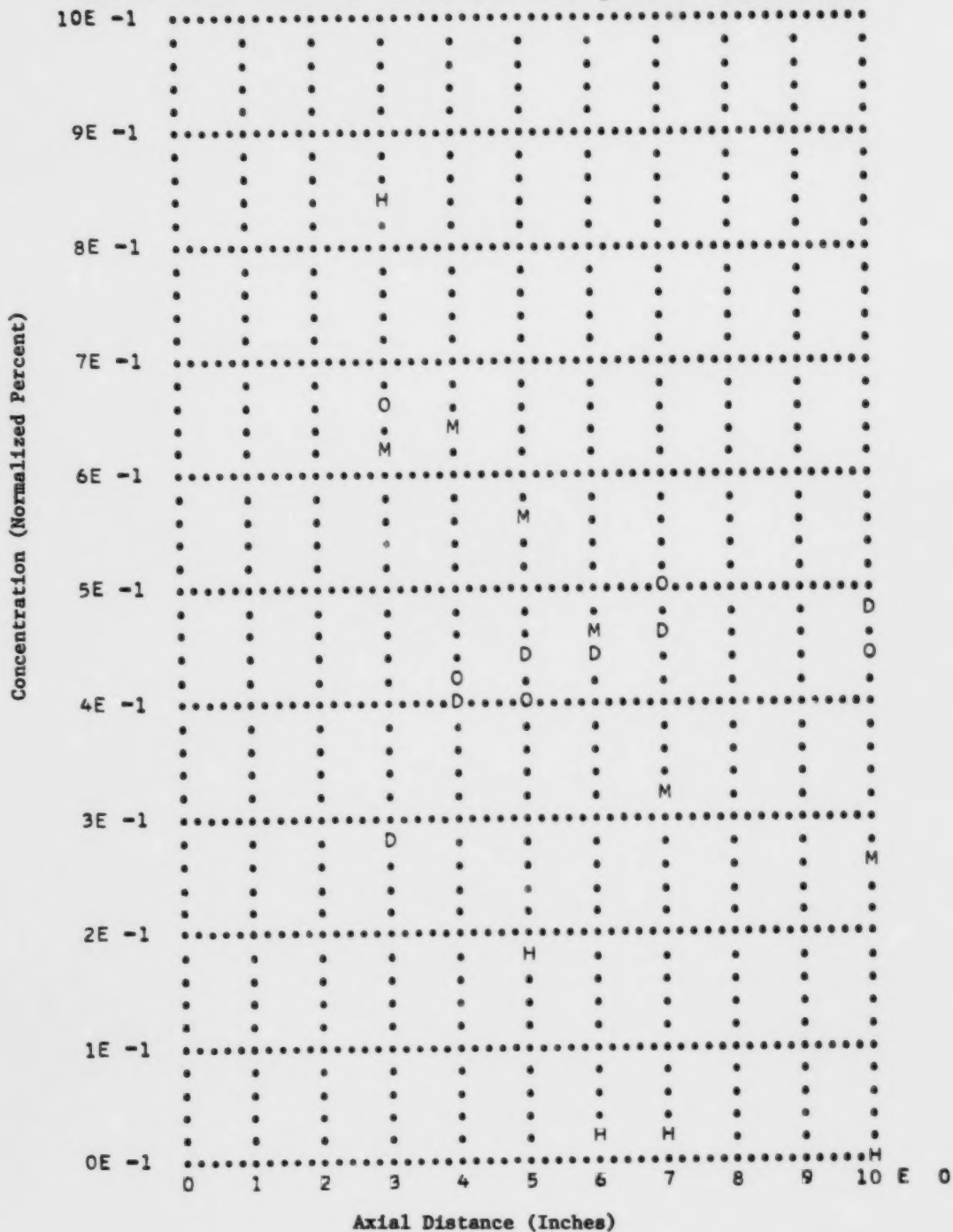
Run Number 128, Stabilized Diffusion Flame Burner (Turbulent), Methane
 Fuel, 160% Stoichiometric Air, Hot Wall 1440C
 Normalized Species Concentrations $\text{CO}_2/15$, $\text{CO}/5$, $\text{O}_2/10$, $\text{HC}/5$
 Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



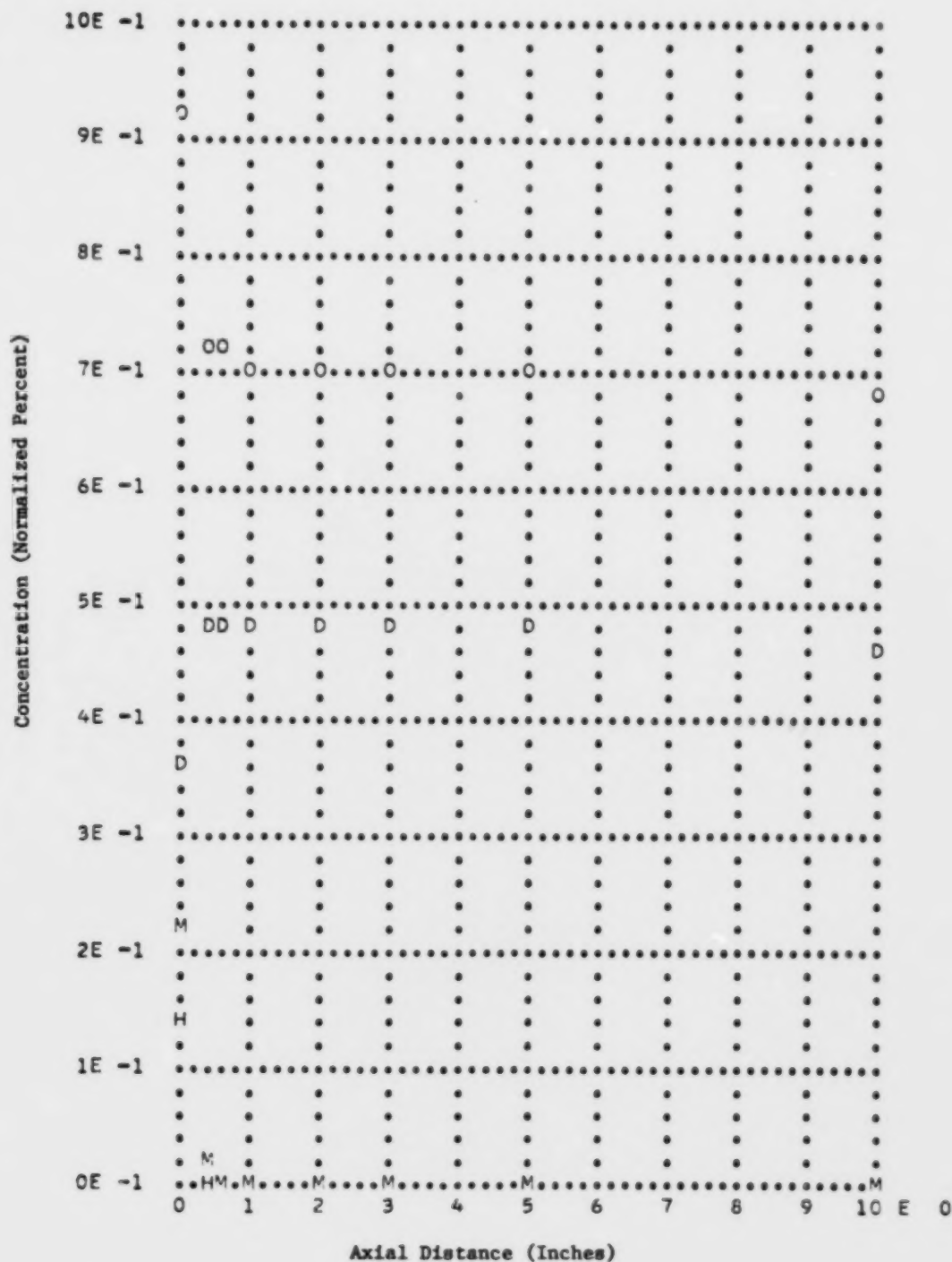
Run Number 128, Stabilized Diffusion Flame Burner (Turbulent), Methane
Fuel, 140% Stoichiometric Air, Hot Wall 1590C

Normalized Species Concentrations $\text{CO}_2/15$, $\text{CO}/5$, $\text{O}_2/10$, $\text{HC}/5$

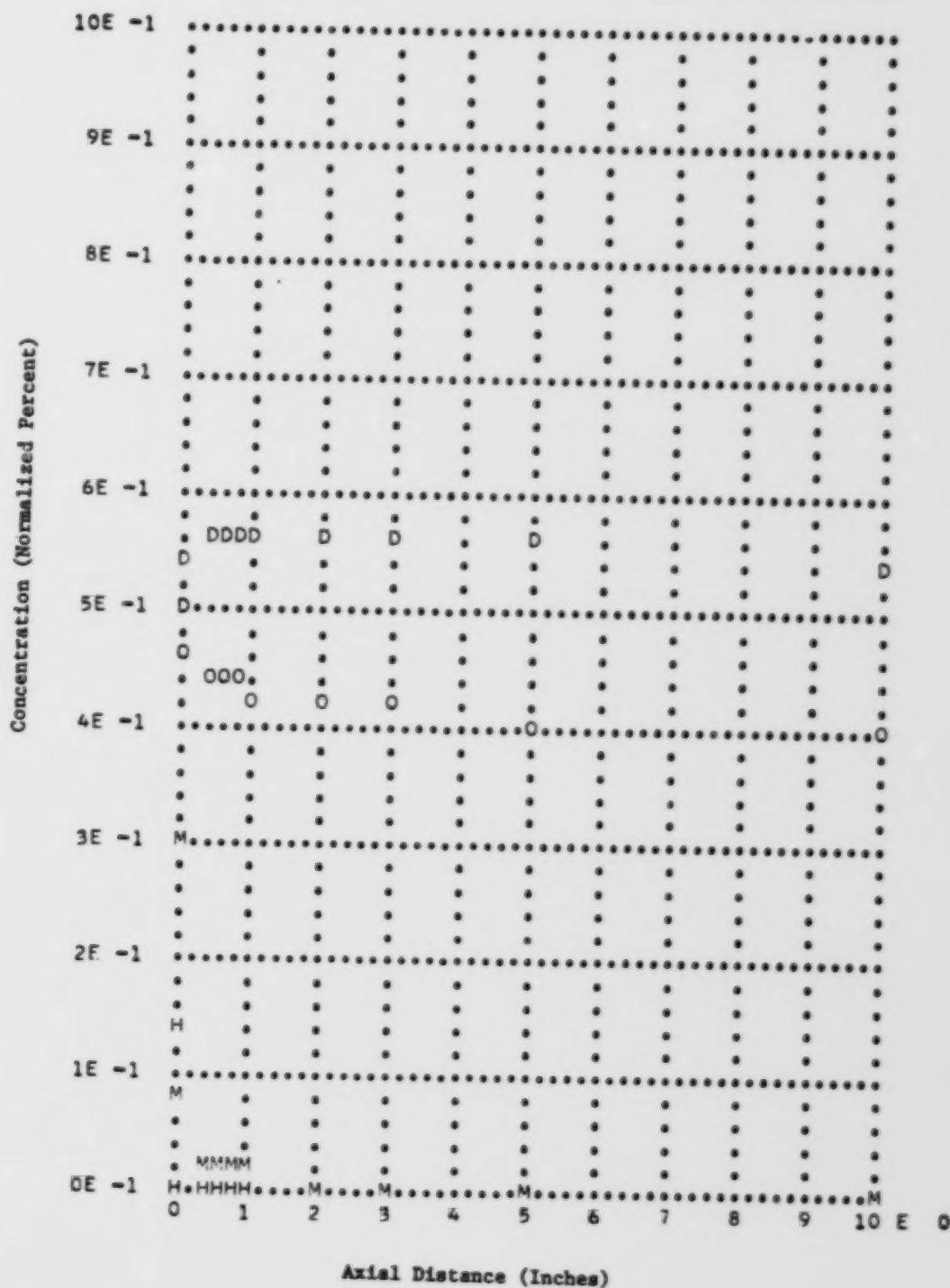
Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



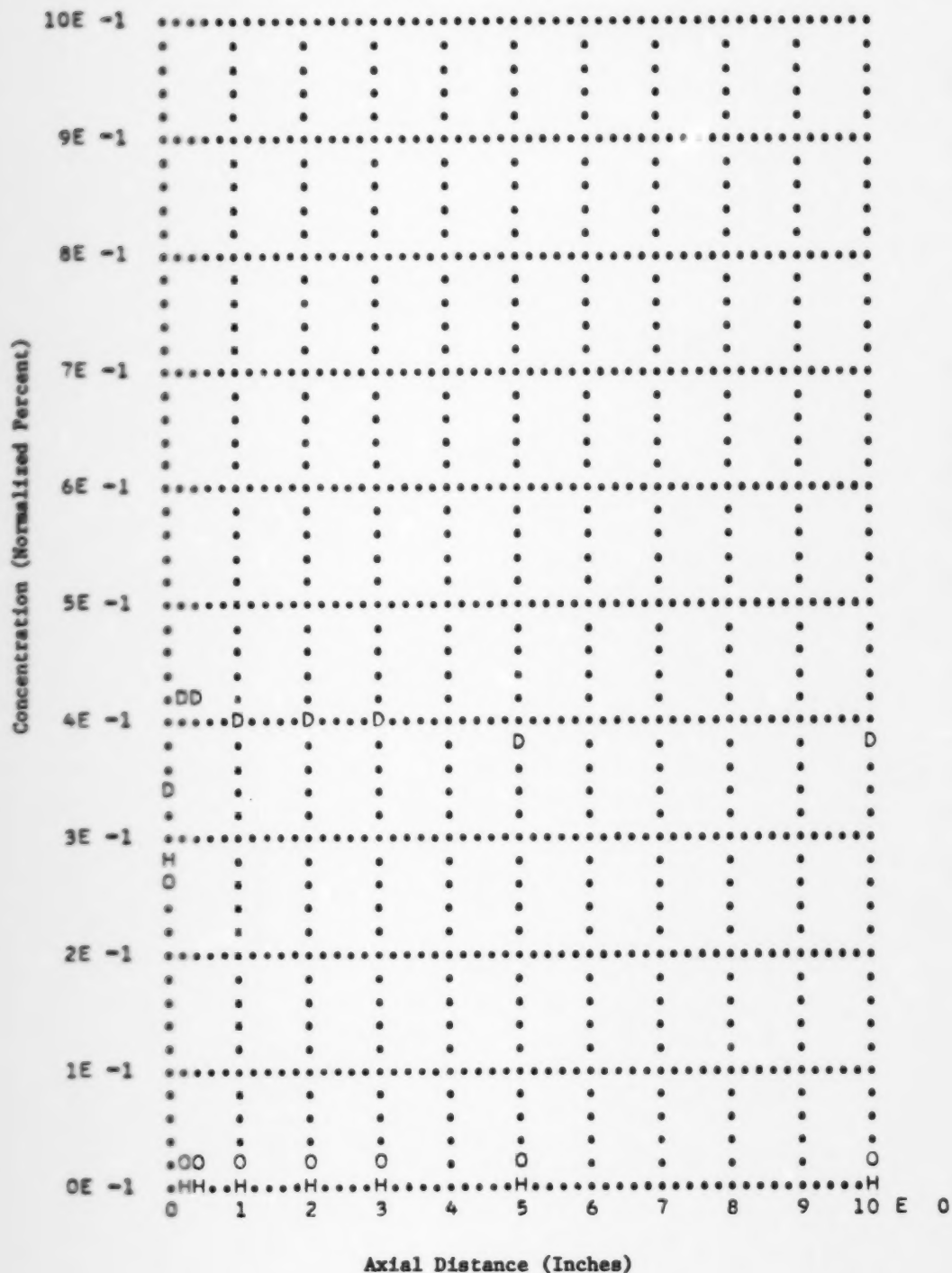
Run Number 130, Premixed Flat Flame Burner (Laminar), Methane Fuel,
 140% Stoichiometric Air, Hot Wall 1585C
 Normalized Species Concentrations $\text{CO}_2/15$, $\text{CO}/5$, $\text{O}_2/10$, $\text{HC}/5$
 Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



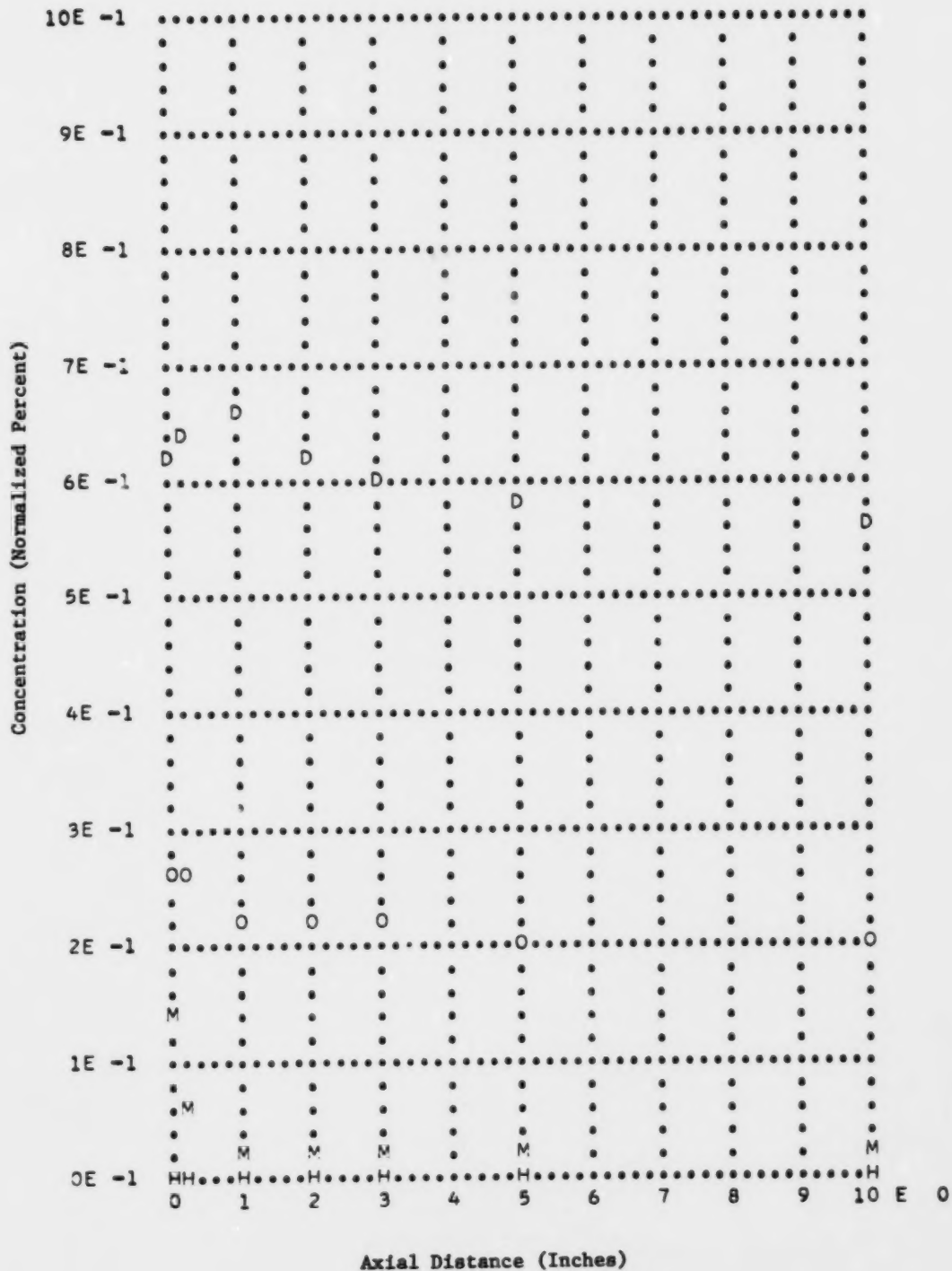
Run Number 131, Premixed Flat Flame Burner (Laminar), Methane Fuel,
 120% Stoichiometric Air, Hot Wall 1770C
 Normalized Species Concentrations $\text{CO}_2/15$, $\text{CO}/5$, $\text{O}_2/10$, $\text{HC}/5$
 Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



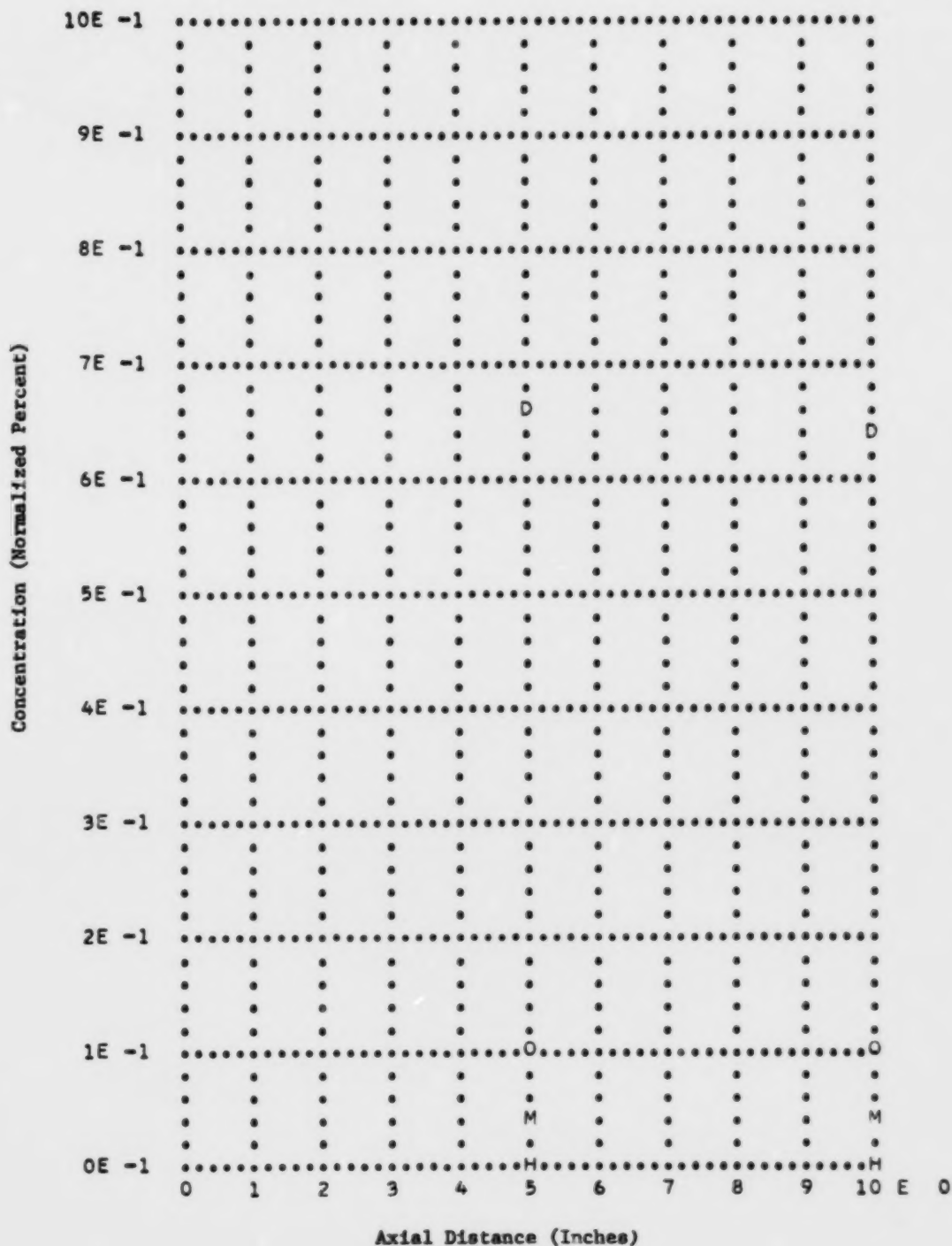
Run Number 131, Premixed Flat Flame Burner (Laminar), Methane Fuel,
 78% Stoichiometric Air, Hot Wall 1770C
 Normalized Species Concentrations $\text{CO}_2/15$, $\text{CO}/5$, $\text{O}_2/10$, $\text{HC}/5$
 Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



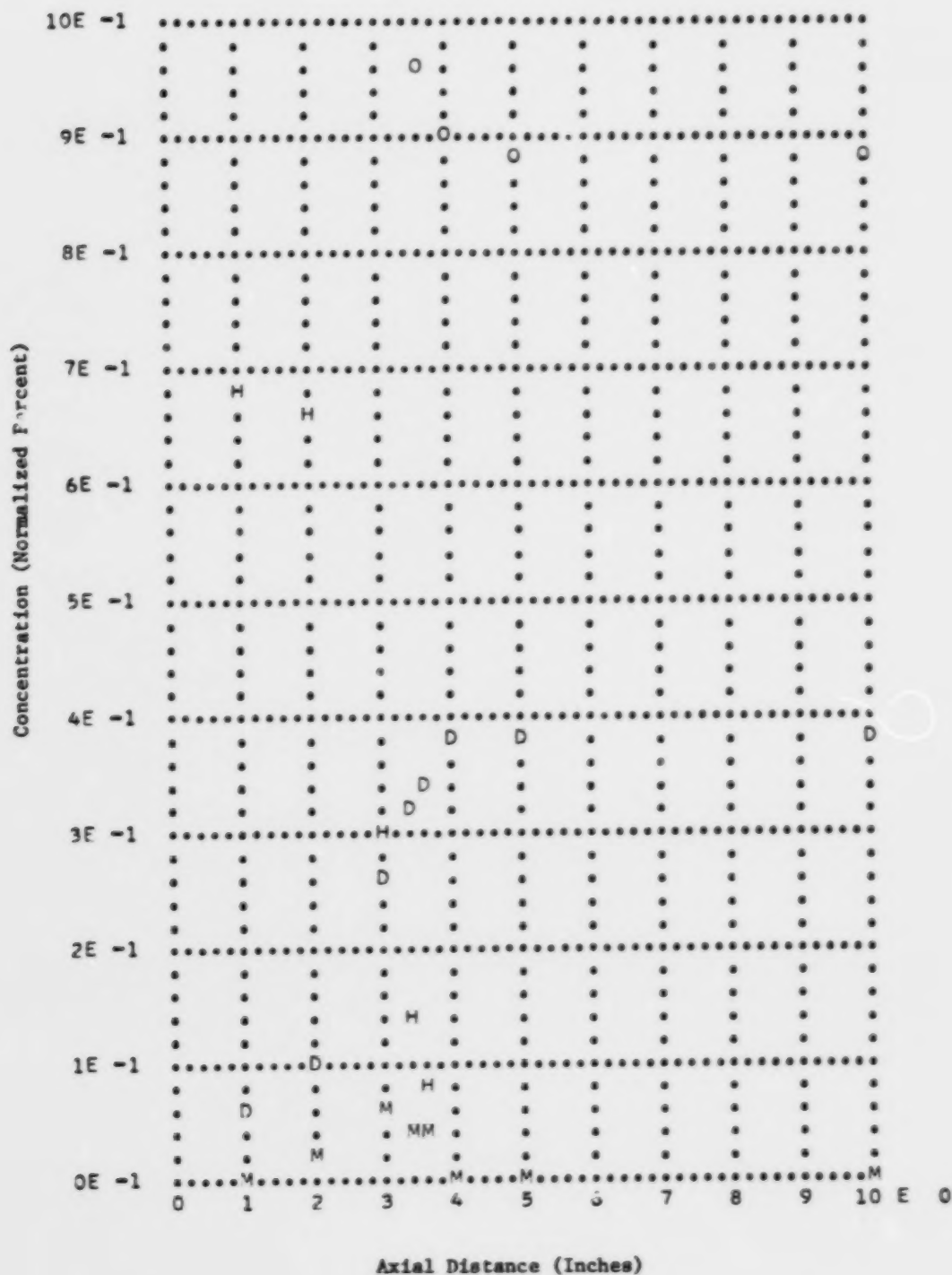
Run Number 131, Premixed Flat Flame Burner (Laminar), Methane Fuel,
111% Stoichiometric Air, Hot Wall 1865C
Normalized Species Concentrations CO₂/15, CO/5, O₂/10, HC/5
Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



Run Number 131, Premixed Flat Flame Burner (Laminar), Methane Fuel,
 101% Stoichiometric Air, Hot Wall 1945C
 Normalized Species Concentrations CO₂/15, CO/5, O₂/10, HC/5
 Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



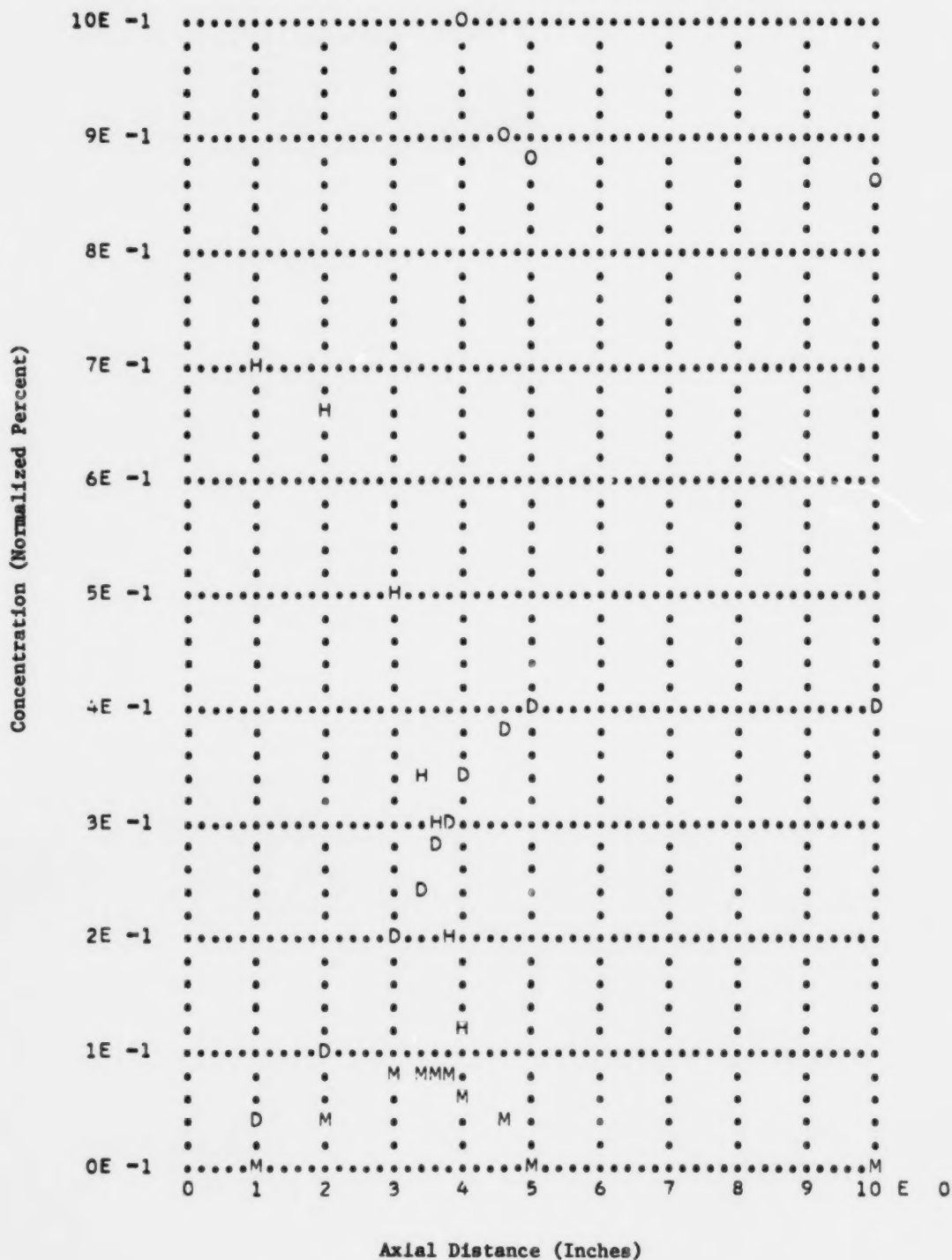
Run Number 132, Premixed Furnace Burner (Laminar), Methane Fuel,
 160% Stoichiometric Air, Hot Wall 1440C
 Normalized Species Concentrations $\text{CO}_2/15$, $\text{CO}/5$, $\text{O}_2/10$, $\text{HC}/5$
 Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



Run Number 133, Premixed Furnace Burner (Turbulent), Methane Fuel,
160% Stoichiometric Air, Hot Wall 1440C

Normalized Species Concentrations $\text{CO}_2/15$, $\text{CO}/5$, $\text{O}_2/10$, $\text{HC}/5$

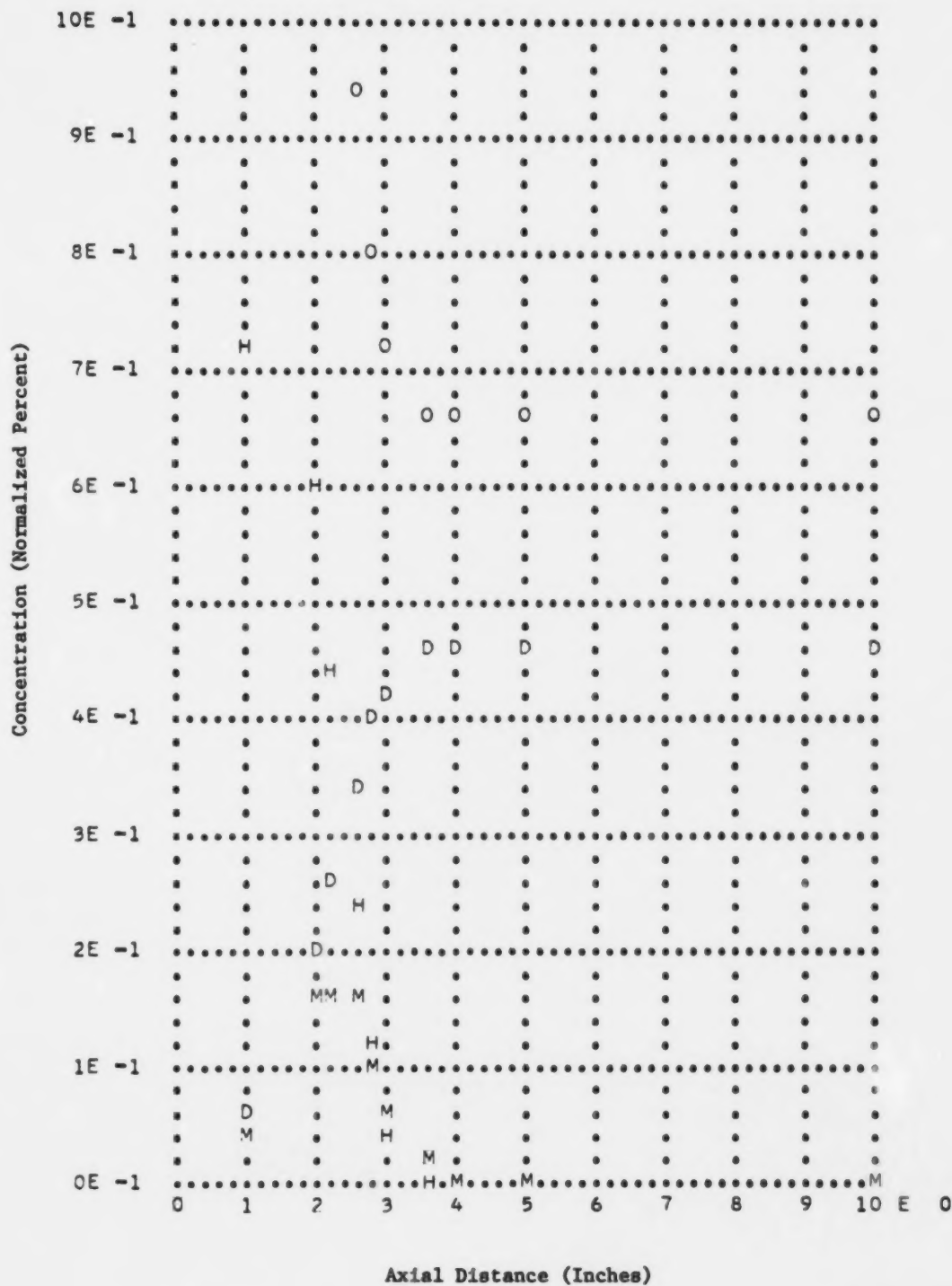
Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



Run Number 133, Premixed Furnace Burner (Turbulent), Methane Fuel,
140% Stoichiometric Air, Hot Wall 1590C

Normalized Species Concentrations $\text{CO}_2/15$, $\text{CO}/5$, $\text{O}_2/10$, $\text{HC}/5$

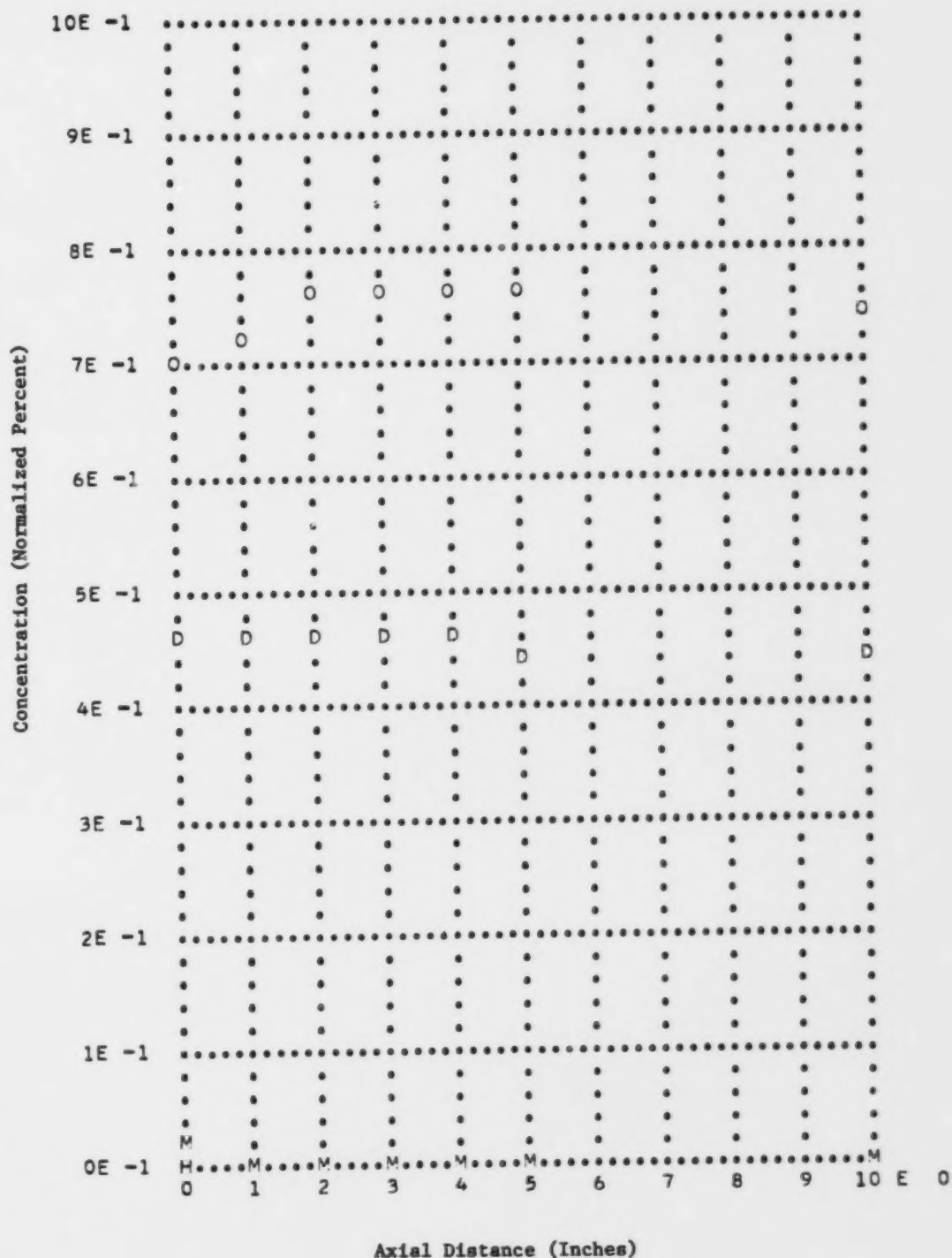
Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



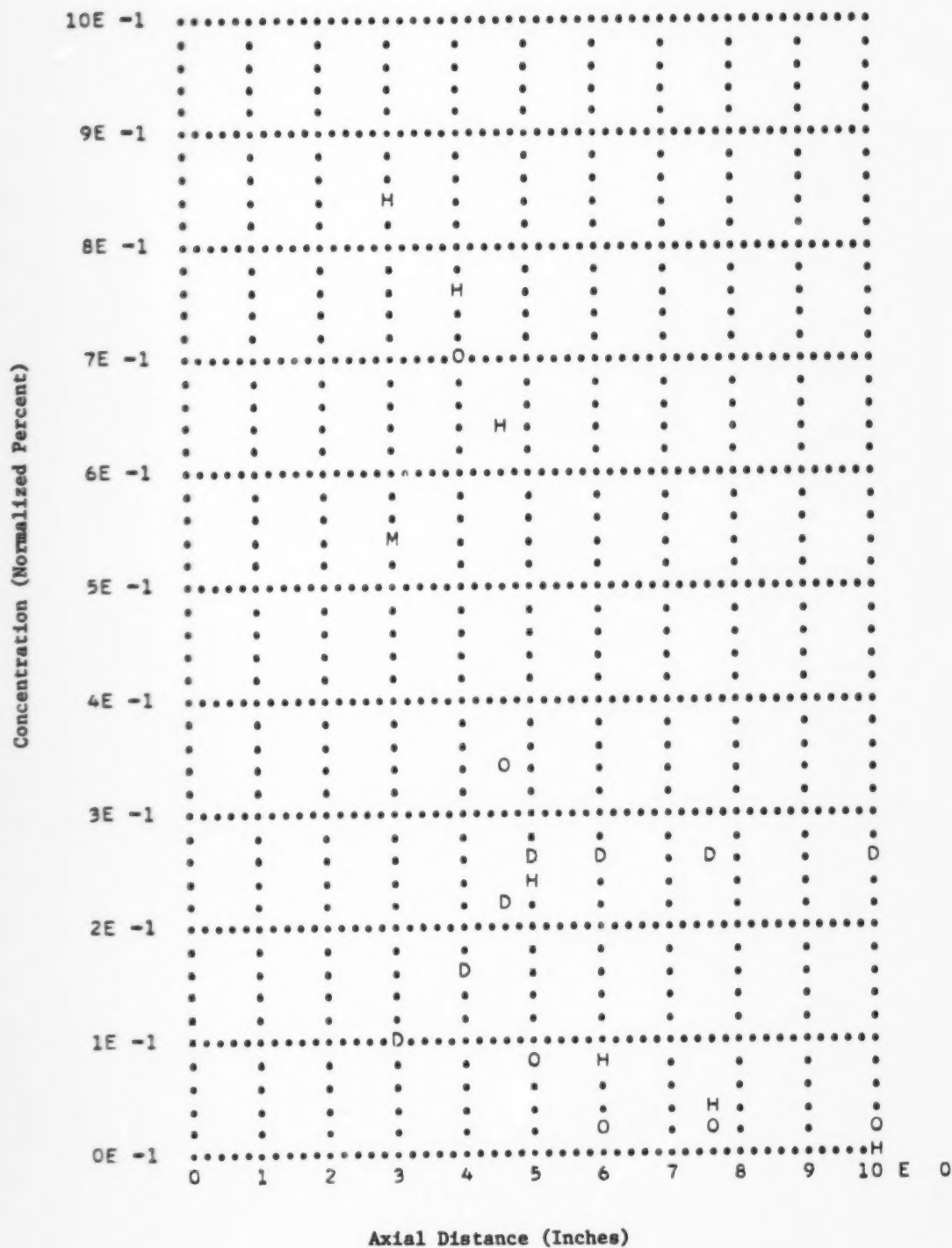
Run Number 134, Premixed Furnace Burner (Laminar), Methane Fuel,
140% Stoichiometric Air, Hot Wall 1585C

Normalized Species Concentrations $\text{CO}_2/15$, $\text{CO}/5$, $\text{O}_2/10$, $\text{HC}/5$

Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H

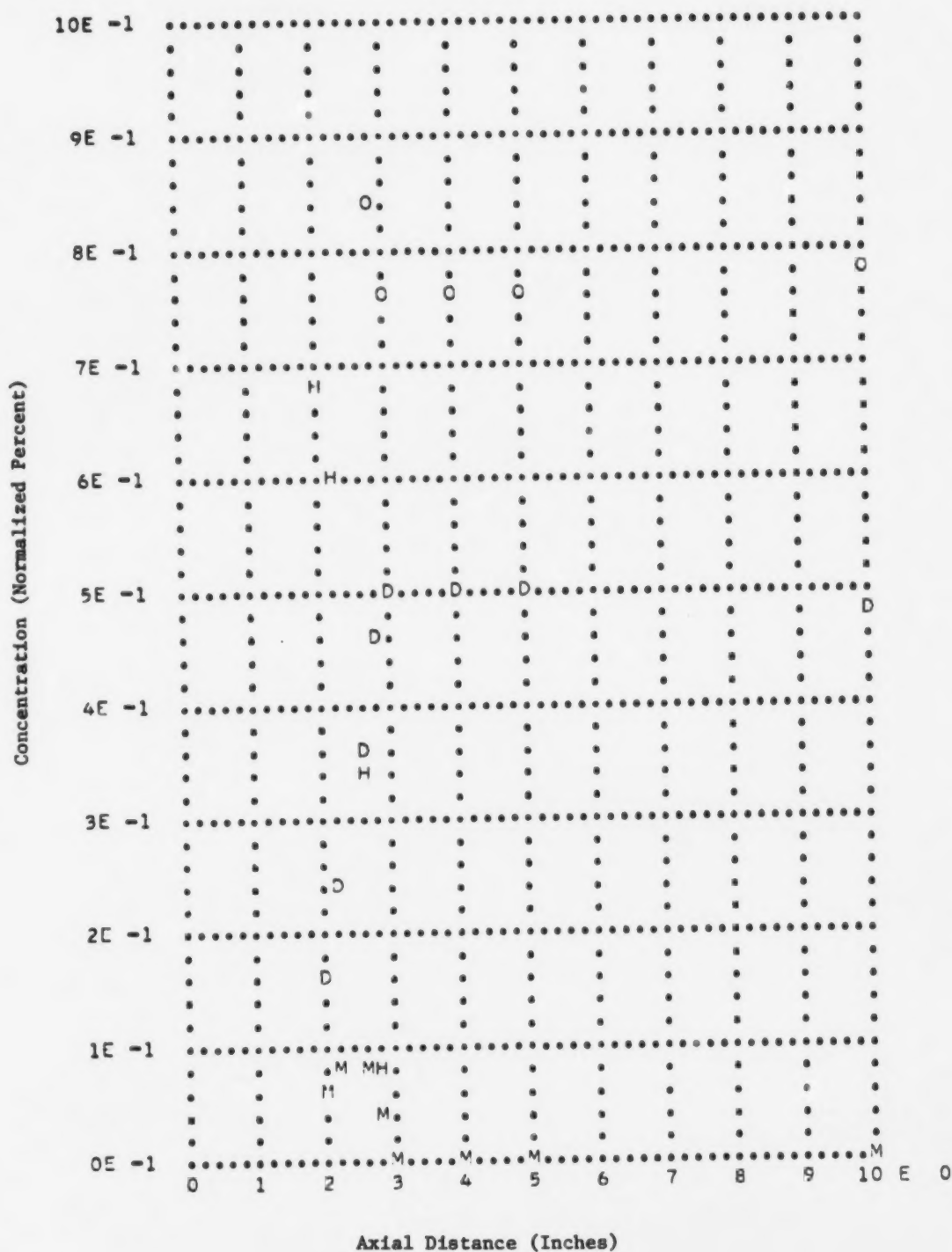


Run Number 134, Premixed Furnace Burner (Laminar), Methane Fuel,
 65% Stoichiometric Air, Hot Wall 1600C
 Normalized Species Concentrations $\text{CO}_2/15$, $\text{CO}/5$, $\text{O}_2/10$, $\text{HC}/5$
 Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



E-48

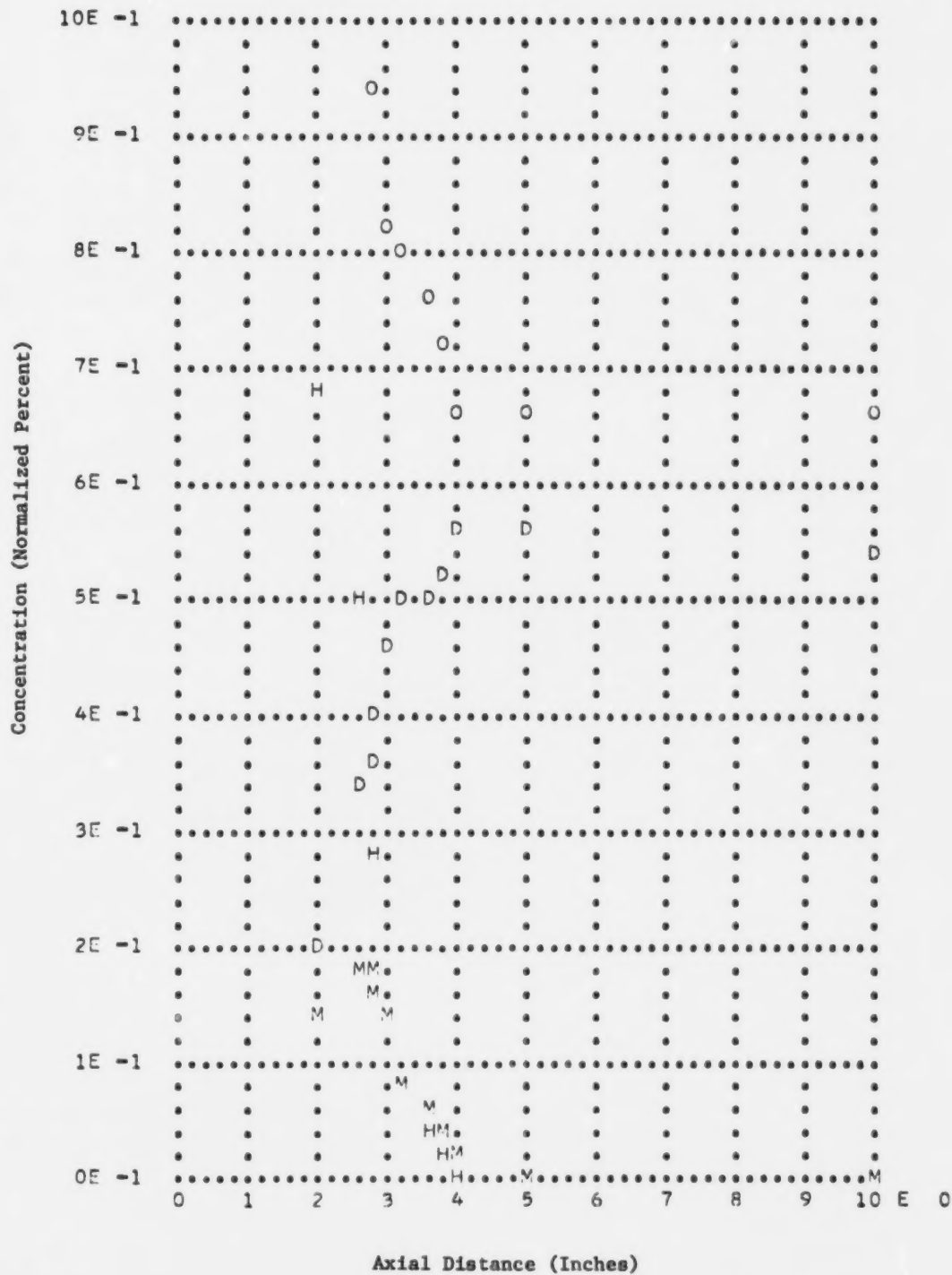
Run Number 135, Premixed Furnace burner (Laminar), Propane Fuel,
 139% Stoichiometric Air, Hot Wall 1625C
 Normalized Species Concentrations CO₂/15, CO/5, O₂/10, HC/5
 Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



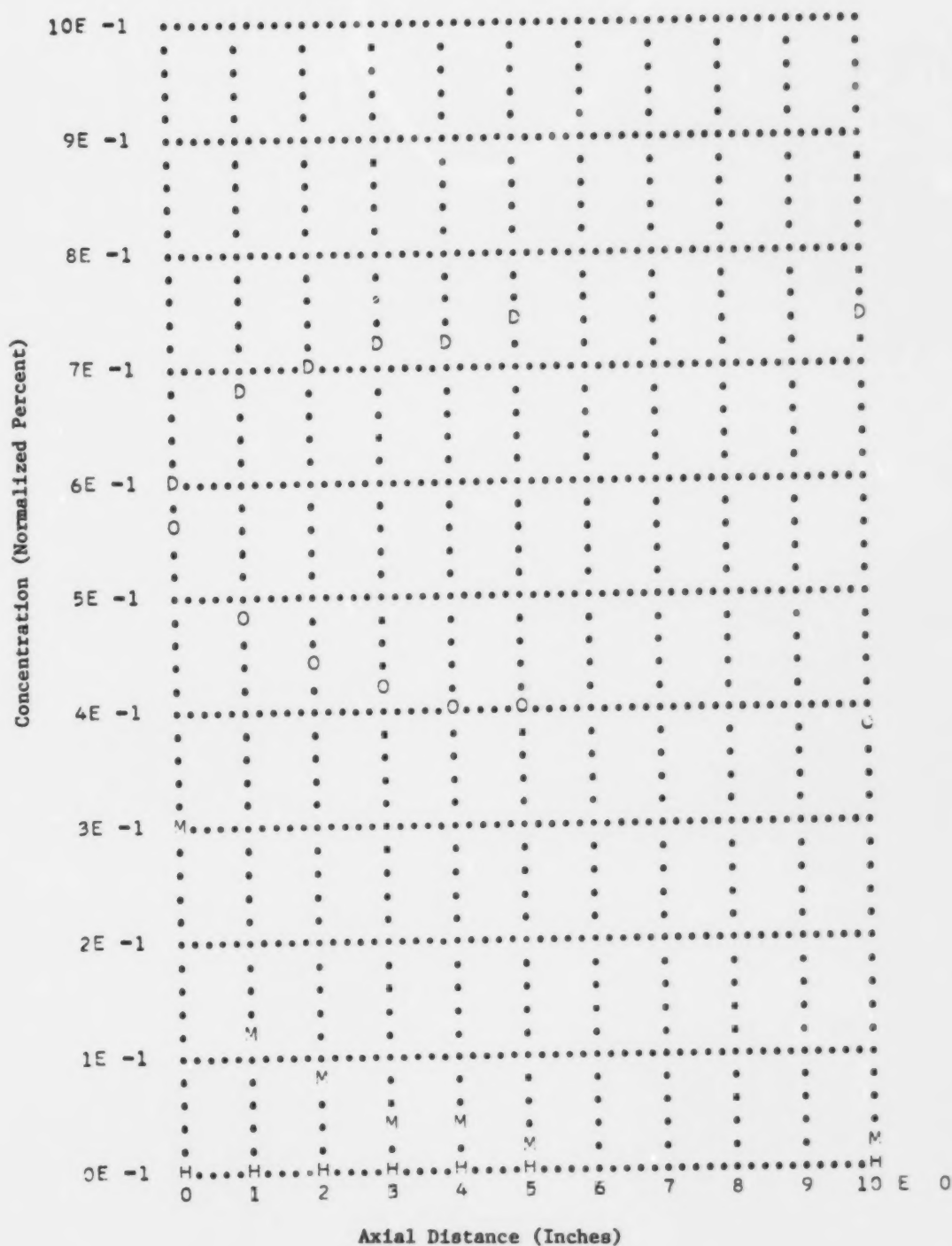
Run Number 136, Premixed Furnace Burner (Turbulent), Propane Fuel,
141% Stoichiometric Air, Hot Wall 1610C

Normalized Species Concentrations CO_2 , $\text{CO}/5$, $\text{O}_2/10$, $\text{HC}/5$

Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



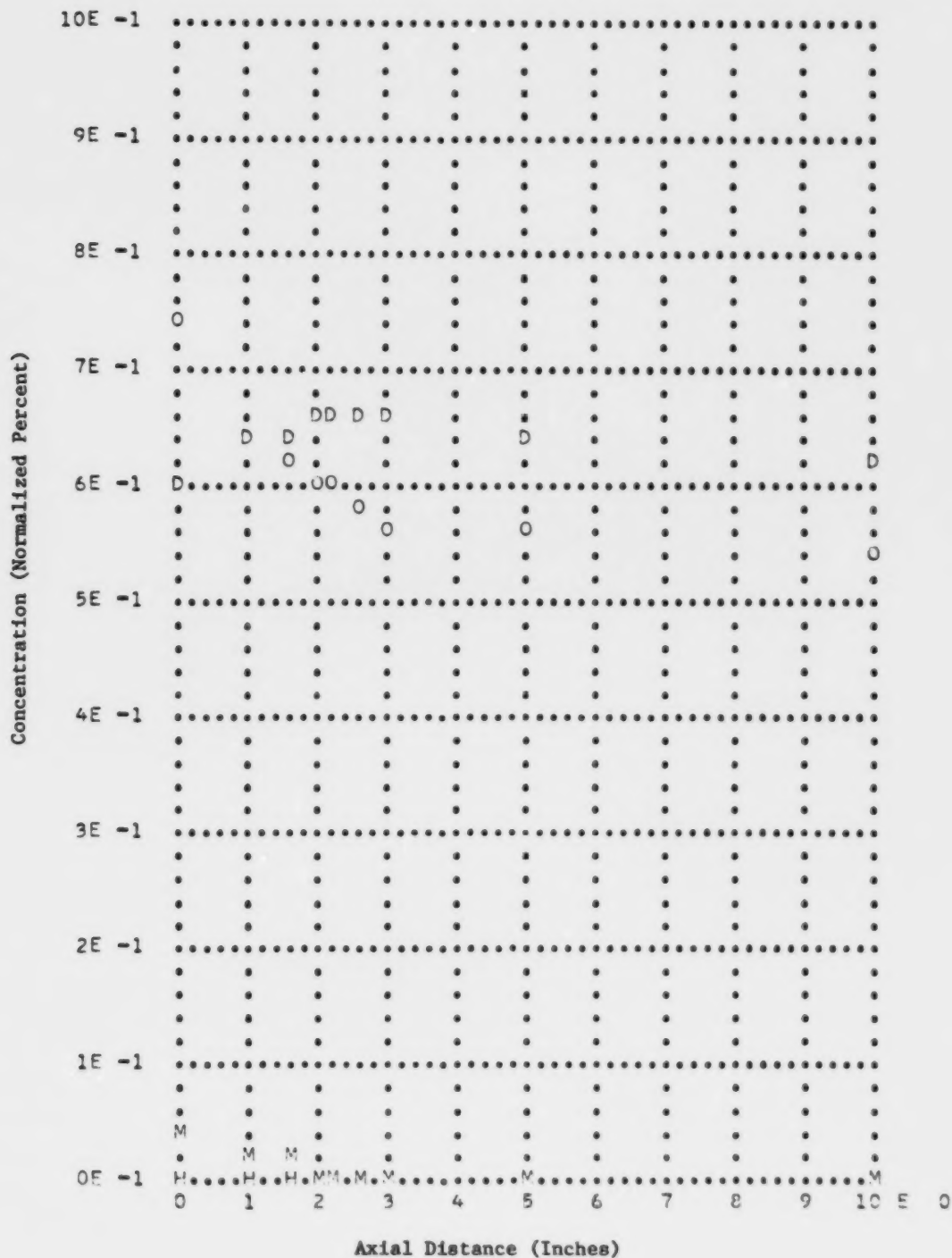
Run Number 137, Premixed Furnace Burner (Turbulent), Propane Fuel,
 121% Stoichiometric Air, Hot Wall 1795C
 Normalized Species Concentrations $\text{CO}_2/15$, $\text{CO}/5$, $\text{O}_2/10$, $\text{HC}/5$
 Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



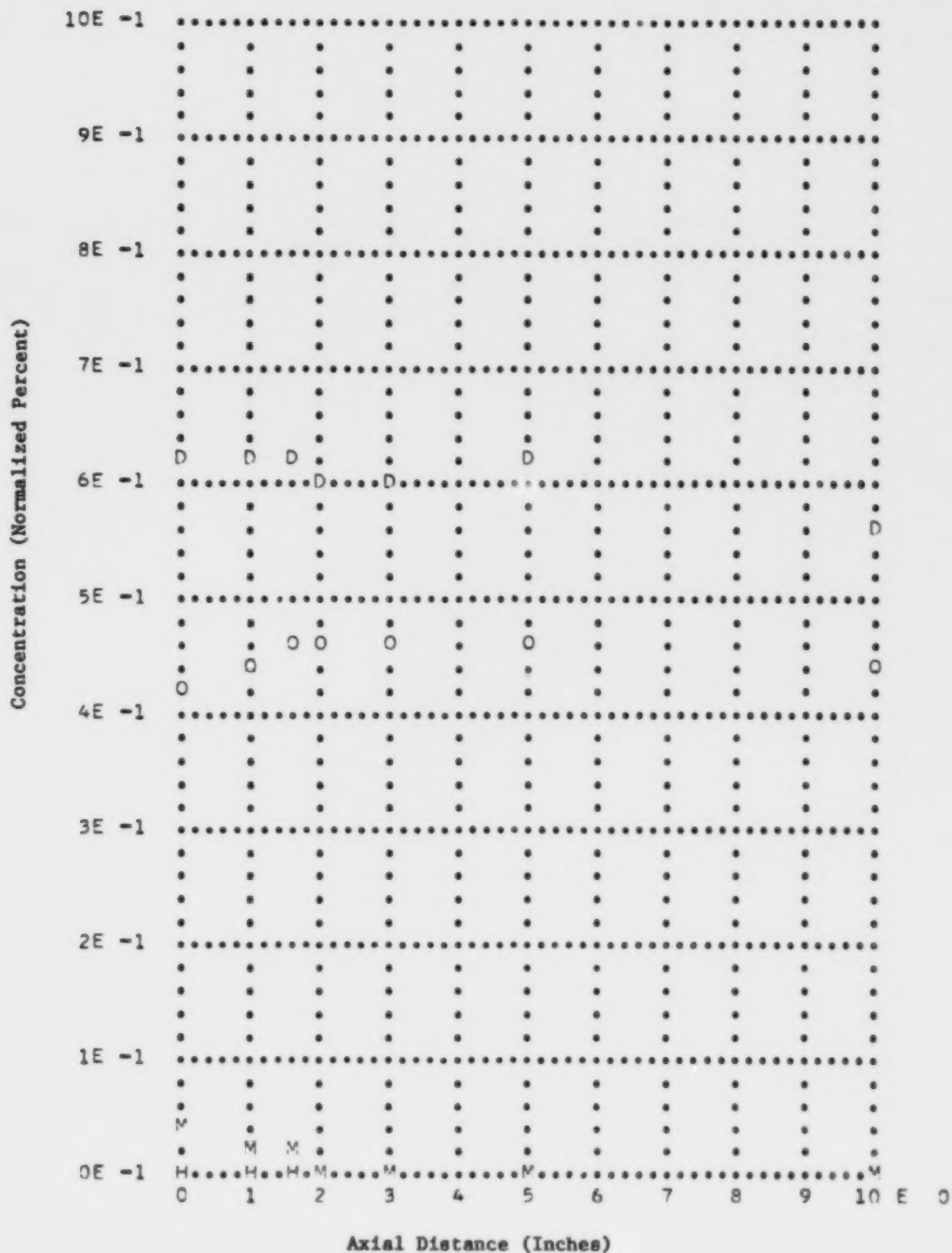
Run Number 138, Premixed Furnace Burner (Laminar), Propane Fuel,
121% Stoichiometric Air, Hot Wall 1795C

Normalized Species Concentrations CO₂/15, CO/5, O₂/10, HC/5

Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



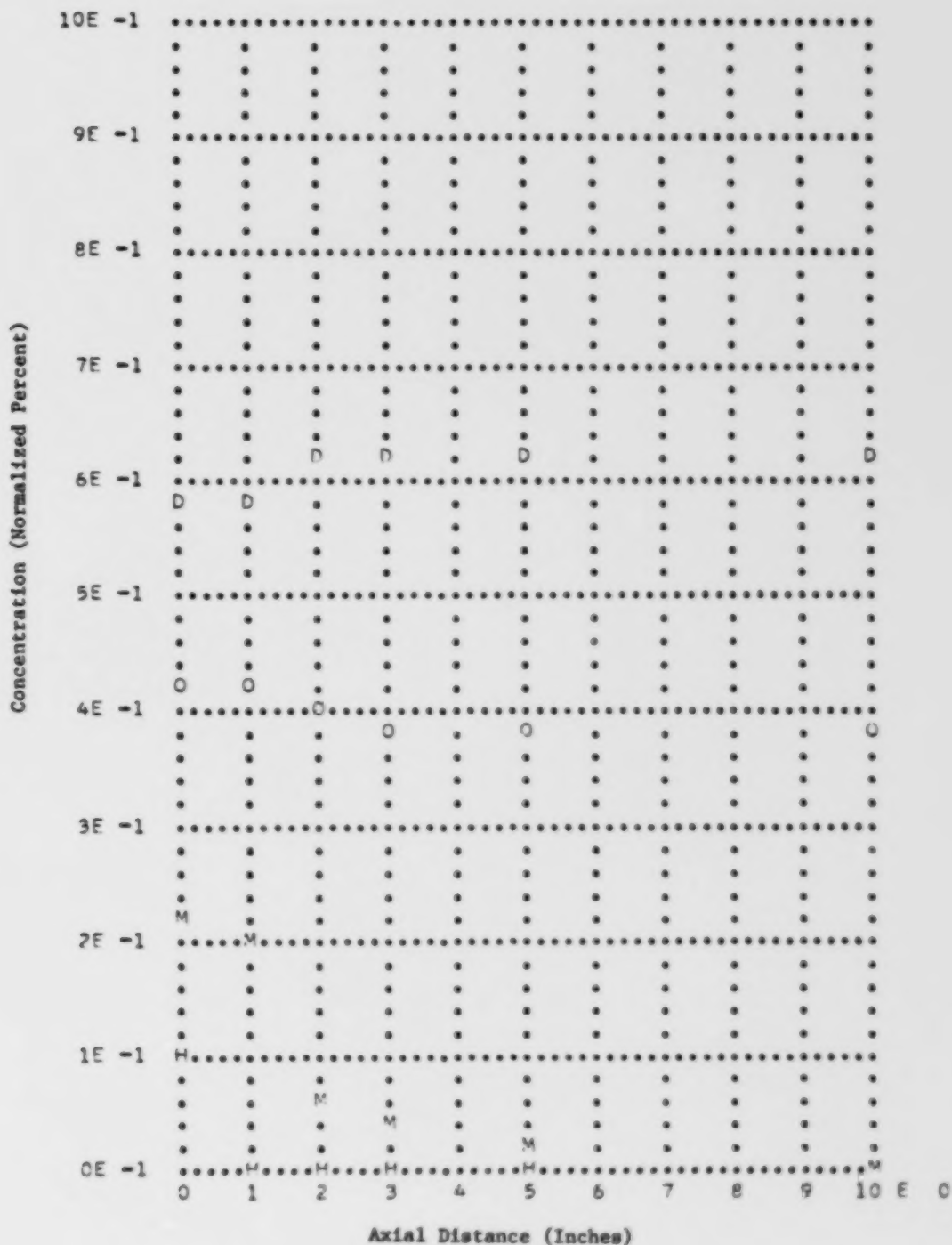
Run Number 139, Premixed Furnace Burner (Laminar), Methane Fuel,
 120% Stoichiometric Air, Hot Wall 1770C
 Normalized Species Concentrations CO₂/15, CO/5, O₂/10, HC/5
 Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



Run Number 140, Premixed Furnace Burner (Turbulent), Methane Fuel,
120% Stoichiometric Air, Hot Wall 1775C

Normalized Species Concentrations $\text{CO}_2/15$, $\text{CO}/5$, $\text{O}_2/10$, $\text{HC}/5$

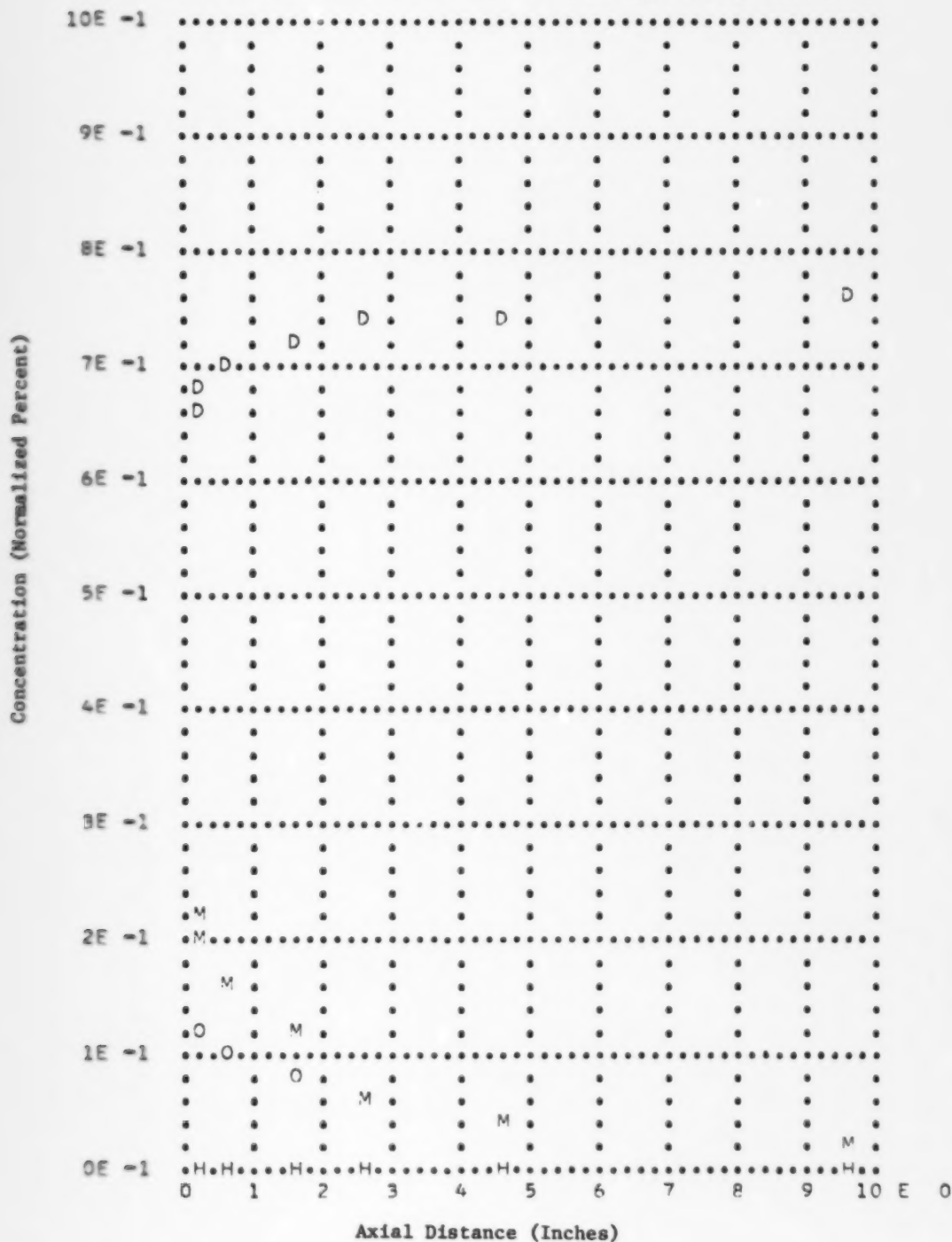
Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



Run Number 141, Premixed Flat Flame Burner (Laminar), Methane Fuel,
101% Stoichiometric Air, Cold Wall

Normalized Species Concentrations $\text{CO}_2/15$, $\text{CO}/5$, $\text{O}_2/10$, $\text{HC}/5$

Legend - Carbon Dioxide=D, Carbon Monoxide=M, Oxygen=O, Hydrocarbon=H



APPENDIX F

DATA LISTINGS

RUN NUMBER 101
PREMIXED FLAT FLAME BURNER
PROPANE
WALL-COLD AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O2 (PCT)	CO (PCT)	CO2 (PCT)	HC (PPM)
0.036	0.854	98.3	10.00	0.00		145		0.06	0.707	13.79	
0.030	0.854	119.4	10.00	0.00		50	57	3.40	0.003	11.73	
0.043	0.854	83.0	10.00	0.00		72		0.04	4.510	10.73	
0.036	0.854	98.3	10.00	0.00		145		0.05			
0.036	0.854	98.3	10.00	0.00				0.05	0.599	13.79	

RUN NUMBER 102
PREMIXED FLAT FLAME BURNER
PROPANE
WALL-COLD AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O2 (PCT)	CO (PCT)	CO2 (PCT)	HC (PPM)
0.021	0.546	106.1	10.05	0.00		98	101	1.15	0.003	13.01	2.
0.021	0.546	106.1	5.05	0.00		88	98	1.10	0.024	13.01	3.
0.021	0.546	106.1	1.05	0.00		75	98	1.20	0.389	12.50	2.
0.022	0.546	100.7	1.05	0.00		88	108	0.43	1.068	12.50	2.
0.022	0.546	100.7	0.40	0.00		50	65	0.53	1.269	12.50	2.
0.022	0.546	100.7	0.30	0.00		40	58	0.54	1.328	12.74	2.
0.021	0.546	106.1	1.00	0.00		63	87	1.40	0.466	12.50	25.
0.021	0.546	106.1	1.00	0.20		74	80	1.35	0.258	12.50	10.
0.021	0.546	106.1	1.00	0.40		65	75	1.25	0.079	13.01	6.
0.021	0.546	106.1	1.00	0.60		80	85	1.20	0.018	13.27	5.
0.021	0.546	106.1	1.00	0.80		88	95	1.50	0.008	13.27	4.
0.021	0.546	106.1	1.00	-0.80		92	97	1.80	0.005	13.01	4.
0.021	0.546	106.1	1.00	-0.60		87	92	1.40	0.010	13.27	4.
0.021	0.546	106.1	1.00	-0.40		70	80	1.25	0.036	13.27	3.
0.021	0.546	106.1	1.00	-0.20		62	70	1.30	0.159	12.75	3.
0.021	0.546	106.1	1.00	0.00		66	83	1.45	0.209	12.75	3.
0.021	0.546	106.1	10.00	0.00		108	110	1.30	0.003	13.01	2.
0.021	0.546	106.1	10.00	0.20		105	107	1.40	0.003	12.75	2.
0.021	0.546	106.1	10.00	0.40		106	108	1.35	0.003	12.75	2.
0.021	0.546	106.1	10.00	0.60		106	107	1.55	0.003	12.50	2.
0.021	0.546	106.1	10.00	0.80		100	103	2.25	0.003	12.50	2.
0.021	0.546	106.1	10.00	1.00		103	107	1.75	0.003	12.24	2.
0.021	0.546	106.1	10.00	-0.80		103	105	2.10	0.003	12.24	2.

RUN NUMBER 102 CONT
PREMIXED FLAT FLAME BURNER
PROPANE
WALL-COLD AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O2 (PCT)	CO (PCT)	CO2 (PCT)	HC (PPM)
0.021	0.546	106.1	10.00	-0.60		106	108	1.50	0.003	12.75	2.
0.021	0.546	106.1	10.00	-0.40		99	102	1.40	0.003	12.75	2.
0.021	0.546	106.1	10.00	-0.20		101	103	1.60	0.003	12.75	2.
0.021	0.546	106.1	10.00	0.00		101	103	1.70	0.003	12.75	2.

RUN NUMBER 103
 PREMIXED FLAT FLAME BURNER
 PROPANE
 WALL-COLD AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O ₂ (PCT)	CO (PCT)	CO ₂ (PCT)	HC (PPM)
0.021	0.546	106.1	10.00	0.00		103	108	1.10	0.003	12.75	2.
0.022	0.546	103.4	10.00	0.00		108	116	0.38	0.007	13.01	3.
0.022	0.546	103.4	10.00	1.00		111	118	0.83	0.005	13.01	1.
0.022	0.546	103.4	10.00	0.80		106	113	1.30	0.004	12.50	1.
0.022	0.546	103.4	10.00	0.60		113	118	0.75	0.004	12.75	1.
0.022	0.546	103.4	10.00	0.40		113	120	0.55	0.005	13.01	1.
0.022	0.546	103.4	10.00	0.20		115	119	0.50	0.006	13.27	1.
0.022	0.546	103.4	10.00	-0.80		113	120	1.30	0.004	12.75	1.
0.022	0.546	103.4	10.00	-0.60		115	120	0.60	0.004	13.01	1.
0.022	0.546	103.4	10.00	-0.40		113	120	0.50	0.005	13.01	1.
0.022	0.546	103.4	10.00	-0.20		111	118	0.60	0.005	13.01	1.
0.022	0.546	103.4	10.00	0.00		111	118	0.50	0.006	13.27	1.
0.022	0.546	103.4	1.00	0.00		60	90	1.10	0.352	12.24	1.
0.022	0.546	103.4	1.00	0.00		88	95	1.25	0.016	13.01	1.
0.022	0.546	103.4	1.00	0.80		95	100	0.80	0.026	13.27	1.
0.022	0.546	103.4	1.00	0.60		65	77	0.70	0.113	13.27	1.
0.022	0.546	103.4	1.00	0.40		62	85	0.75	0.337	12.75	1.
0.022	0.546	103.4	1.00	0.20		76	108	0.85	0.028	12.50	1.
0.022	0.546	103.4	1.00	-0.80		97	100	1.20	0.009	13.01	2.
0.022	0.546	103.4	1.00	-0.60		93	98	0.35	0.036	13.27	3.
0.022	0.546	103.4	1.00	-0.40		67	80	0.45	0.199	13.27	1.
0.022	0.546	103.4	1.00	-0.20		75	95	0.75	0.455	12.50	1.
0.022	0.546	103.4	1.00	0.00		75	95	0.73	0.464	12.50	1.

RUN NUMBER 103 CONT
PREMIXED FLAT FLAME BURNER
PROPANE
WALL-COLD AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O ₂ (PCT)	CO (PCT)	CO ₂ (PCT)	HC (PPM)
0.018	0.546	122.0	1.00	0.00		45	60	4.00	0.075	10.98	1.
0.018	0.546	122.0	1.00	0.20		40	54	3.90	0.072	11.23	2.
0.018	0.546	122.0	1.00	0.40		47	55	3.90	0.059	10.98	1.
0.018	0.546	122.0	1.00	0.60		38	43	3.90	0.025	11.23	1.
0.018	0.546	122.0	1.00	0.80		42	43	4.00	0.004	11.48	1.
0.018	0.546	122.0	1.00	1.00		41	45	4.20	0.003	11.48	1.
0.018	0.546	122.0	1.00	-0.80		43	46	4.00	0.005	11.48	1.
0.018	0.546	122.0	1.00	-0.60		37	42	3.90	0.006	11.48	1.
0.018	0.546	122.0	1.00	-0.40		31	39	3.95	0.020	11.23	1.
0.018	0.546	122.0	1.00	-0.20		37	42	3.95	0.072	10.98	1.
0.018	0.546	122.0	10.00	0.00		50	50	3.90	0.003	10.98	1.
0.018	0.546	122.0	10.00	0.20		50	51	4.00	0.003	11.23	1.
0.018	0.546	122.0	10.00	0.40		49	50	4.00	0.003	10.98	1.
0.018	0.546	122.0	10.00	0.60		50	51	4.20	0.002	11.23	1.
0.018	0.546	122.0	10.00	0.80		47	48	4.60	0.002	10.73	1.
0.018	0.546	122.0	10.00	1.00		46	47	4.70	0.002	10.98	3.
0.018	0.546	122.0	10.00	-0.80		45	46	5.00	0.002	10.73	3.
0.018	0.546	122.0	10.00	-0.60		49	50	4.30	0.003	11.23	2.
0.018	0.546	122.0	10.00	-0.40		49	50	4.20	0.003	11.23	3.
0.018	0.546	122.0	10.00	-0.20		50	51	4.10	0.003	11.23	8.
0.018	0.546	122.0	10.00	0.00		39	48	4.00	0.005	11.23	9.
0.018	0.546	122.0	2.00	0.00		36	45	4.10	0.031	10.98	3.
0.018	0.546	122.0	1.00	0.00		31	37	4.20	0.066	10.73	5.

RUN NUMMR 103 CONT
PREMIXED FLAT FLAME BURNER
PROPANE
WALL-COLD AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O2 (PCT)	CO (PCT)	CO2 (PCT)	HC (PPM)
0.018	0.546	122.0	1.00	0.20		32	36	4.20	0.073	10.98	1.
0.018	0.552	123.3	1.00	0.80		31	35	4.40	0.005	10.98	7.
0.019	0.552	123.3	1.00	0.60				4.30	0.014	10.98	7.
0.019	0.552	123.3	1.00	1.00				4.60	0.004	10.98	7.
0.018	0.552	123.3	1.00	0.40				4.30	0.046	10.98	7.
0.019	0.552	123.3	1.00	-0.20				4.30	0.044	10.98	8.
0.019	0.546	122.0	1.00	-0.20				3.90	0.066	10.98	7.
0.018	0.546	122.0	1.00	-0.40				3.90	0.023	10.98	7.
0.018	0.546	122.0	1.00	-0.20				3.90	0.060	10.98	7.
0.018	0.546	122.0	1.00	-0.30				3.90	0.042	10.98	7.

RUN NUMBER 104
PREMIXED FLAT FLAME BURNER
PROPANE
WALL-COLD AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O ₂ (PCT)	CO (PCT)	CO ₂ (PCT)	HC (PPM)
0.018	0.546	122.0	1.00	0.00		32	41	3.90	0.076	10.73	1.
0.018	0.546	122.0	1.00	-0.80				4.50	0.004	10.98	1.
0.018	0.546	122.0	1.00	-0.60				4.10	0.006	10.98	2.
0.018	0.546	122.0	1.00	-0.40				3.95	0.018	10.98	2.
0.018	0.546	122.0	1.00	-0.20				3.97	0.055	10.73	2.
0.018	0.546	122.0	1.00	0.00				3.90	0.079	10.73	2.
0.018	0.546	122.0	1.00	0.20				4.00	0.073	10.49	2.
0.018	0.546	122.0	1.00	0.40				4.05	0.046	10.73	2.
0.018	0.546	122.0	1.00	0.60				4.00	0.016	10.98	2.
0.018	0.546	122.0	1.00	0.80				4.20	0.006	10.98	2.
0.018	0.546	122.0	1.00	1.00				4.60	0.004	10.73	2.
0.024	0.546	93.5	1.00	1.00		63		0.15	1.927	12.75	3.
0.024	0.546	93.5	1.00	0.80		65		0.05	2.012	12.24	3.
0.024	0.546	93.5	1.00	0.60		60		0.03	2.012	12.24	4.
0.024	0.546	93.5	1.00	0.40		72		0.04	2.273	11.99	4.
0.024	0.546	93.5	1.00	0.20		93		0.08	2.724	11.23	4.
0.024	0.546	93.5	1.00	0.00		78		0.07	2.632	11.48	4.
0.024	0.546	93.5	1.00	-0.20		70		0.05	2.362	11.48	4.
0.024	0.546	93.5	1.00	-0.40		60		0.03	2.099	11.99	4.
0.024	0.546	93.5	1.00	-0.60		67		0.04	1.927	12.50	4.
0.024	0.546	93.5	1.00	-0.80		69		0.23	1.421	12.75	4.
0.024	0.546	93.5	1.00	0.00		77		0.08	2.451	11.48	4.
0.024	0.546	93.5	0.70	0.00		73		0.09	2.451	11.48	4.

RUN NUMBR 104 CONT
PREMIXED FLAT FLAME BURNER
PROPANE
WALL-COLD AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O2 (PCT)	CO (PCT)	CO2 (PCT)	HC (PPM)
0.024	0.546	93.5	0.50	0.00		65		0.16	2.451	11.48	4.
0.024	0.546	93.5	0.30	0.00		55		0.24	2.451	11.48	4.
0.024	0.546	93.5	0.20	0.00		48		0.27	2.541	11.48	4.
0.024	0.546	93.5	0.10	0.00		38		0.46	2.632	11.23	80.
0.024	0.546	93.5	0.05	0.00		20		1.00	3.007	10.49	1200.
0.024	0.546	93.5	10.00	0.00		84		0.03	1.757	12.75	2.
0.024	0.546	93.5	10.00	0.20		83		0.03	1.841	12.24	2.
0.024	0.546	93.5	10.00	0.40		81		0.08	1.757	12.24	2.
0.024	0.546	93.5	10.00	0.60		80		0.10	1.672	12.24	2.
0.024	0.546	93.5	10.00	0.80		70		0.50	1.337	12.24	2.
0.024	0.546	93.5	10.00	1.00		66		0.50	1.421	12.24	2.
0.024	0.546	93.5	10.00	-0.80		63		0.80	1.421	12.24	2.
0.024	0.546	93.5	10.00	-0.60		80		0.20	1.588	12.24	2.
0.024	0.546	93.5	10.00	-0.40		83		0.07	1.757	12.24	2.
0.024	0.546	93.5	10.00	-0.20		86		0.04	1.757	11.99	2.
0.024	0.546	93.5	10.00	0.00		86		0.03	1.757	11.99	2.
0.027	0.546	83.2	10.00	0.00		61		0.03	4.274	9.99	2.
0.027	0.546	83.2	10.00	0.20		62		0.03	4.274	10.24	2.
0.027	0.546	83.2	10.00	0.40		64		0.04	4.158	10.24	2.
0.027	0.546	83.2	10.00	0.60		64		0.09	4.274	10.24	2.
0.027	0.546	83.2	10.00	0.80		55		0.40	3.824	10.24	2.
0.027	0.546	83.2	10.00	1.00		56		0.38	4.045	10.24	2.
0.027	0.546	83.2	10.00	-0.80		49		0.70	3.824	9.99	2.

RUN NUMBER 104 CONT
PREMIXED FLAT FLAME BURNER
PROPANE
WALL-COLD AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O2 (PCT)	CO (PCT)	CO2 (PCT)	HC (PPM)
0.027	0.546	83.2	10.00	-0.60		65		0.18	4.045	10.24	2.
0.027	0.546	83.2	10.00	-0.40		66		0.05	4.158	10.24	2.
0.027	0.546	83.2	10.00	-0.20		65		0.03	4.158	10.24	2.
0.027	0.546	83.2	10.00	0.00		65		0.02	4.274	10.24	1.
0.027	0.546	83.2	10.00	0.00		63		0.01	4.882	9.51	1.
0.027	0.546	83.2	1.00	0.20		68		0.01	4.882	9.51	1.
0.027	0.546	83.2	1.00	0.40		67		0.01	5.011	9.51	2.
0.027	0.546	83.2	1.00	0.60		56		0.01	4.391	10.24	10.
0.027	0.546	83.2	1.00	0.80		54		0.05	4.158	10.73	15.
0.027	0.546	83.2	1.00	1.00		51		0.17	3.824	11.23	15.
0.027	0.546	83.2	1.00	-0.80		54		0.20	3.933	10.98	4.
0.027	0.546	83.2	1.00	-0.60		63		0.04	4.158	10.49	5.
0.027	0.546	83.2	1.00	-0.40		60		0.02	4.391	10.24	4.
0.027	0.546	83.2	1.00	-0.20		65		0.02	4.756	9.51	1.
0.027	0.546	83.2	1.00	0.00		66		0.03	5.011	9.51	1.
0.027	0.546	83.2	0.70	0.00		62		0.03	4.756	9.75	1.
0.027	0.546	83.2	0.50	0.00		59		0.03	4.756	9.51	1.
0.027	0.546	83.2	0.30	0.00		55		0.04	4.756	9.51	1.
0.027	0.546	83.2	0.20	0.00		52		0.05	4.632	9.75	1.
0.027	0.546	83.2	0.10	0.00		46		0.18	4.632	9.51	600.
0.027	0.546	83.2	0.00	-0.20		14		3.60	4.274	7.60	20000.
0.027	0.546	83.2	0.05	-0.20		25		1.75	4.632	8.54	8500.
0.027	0.546	83.2	0.10	-0.20		51		0.08	4.510	9.75	550.

RUN NUMBER 105
STABILIZED DIFFUSION BURNER
METHANE
WALL-COLD AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O2 (PCT)	CO (PCT)	CO2 (PCT)	HC (PPM)
0.225	2.172	101.2	10.00	-0.03		40	44	0.05	0.304	11.23	1.
0.225	2.172	101.2	10.00	0.80		28	33	0.08	0.017	10.73	1.
0.225	2.172	101.2	10.00	0.60		31	35	0.07	0.045	10.73	1.
0.225	2.172	101.2	10.00	0.40		33	38	0.05	0.147	10.98	1.
0.225	2.172	101.2	10.00	0.20		35	41	0.05	0.204	10.98	1.
0.225	2.172	101.2	10.00	0.00		34	41	0.04	0.304	10.98	1.
0.225	2.172	101.2	10.00	-0.20		33	47	0.04	0.285	10.98	1.
0.225	2.172	101.2	10.00	-0.40		33	41	0.04	0.304	10.98	1.
0.225	2.172	101.2	10.00	-0.60		30	38	0.05	0.190	10.73	1.
0.225	2.172	101.2	10.00	-0.80		26	34	0.06	0.073	10.98	1.
0.225	2.172	101.2	10.00	-0.86		27	34	0.07	0.050	10.98	1.
0.225	2.172	101.2	5.00	0.00		25	33	0.05	0.501	9.99	900.
0.225	2.172	101.2	5.00	0.20		22	30	0.06	0.501	10.24	300.
0.225	2.172	101.2	5.00	0.00		37	46	1.25	1.689	9.99	400.
0.225	2.172	101.2	5.00	0.20		35	42	3.50	1.039	10.24	110.
0.225	2.172	101.2	5.00	0.40		28	35	2.60	0.493	10.24	20.
0.225	2.172	101.2	5.00	0.60		23	27	4.00	0.109	9.75	20.

RUN NUMBER 106
STABILIZED DIFFUSION BURNER
METHANE
WALL-COLD AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O2 (PCT)	CO (PCT)	CO2 (PCT)	HC (PPM)
0.225	2.172	101.2	10.00	0.00		39	48		0.151	10.73	1.
0.225	2.172	101.2	10.00	0.20		36	43		0.089	10.49	1.
0.225	2.172	101.2	10.00	0.40		34	38		0.046	10.49	1.
0.225	2.172	101.2	10.00	0.60		26	35		0.020	10.24	1.
0.225	2.172	101.2	10.00	-0.60		34	41		0.102	10.49	1.
0.225	2.172	101.2	10.00	-0.40		36	46		0.124	10.49	1.
0.225	2.172	101.2	10.00	-0.20		49	45		0.143	10.73	1.
0.225	2.172	101.2	10.00	0.00		40	44		0.131	10.73	1.
0.225	2.172	101.2	5.40	0.00		33	39		1.068	10.24	200.
0.225	2.172	101.2	5.00	0.00		33	49		1.537	9.99	2000.
0.225	2.172	101.2	4.00	0.00		2	19		1.387	5.97	25000.
0.225	2.172	101.2	3.50	0.00		1	9		0.707	3.54	25000.
0.225	2.172	101.2	2.00	0.00		0	1		0.031	0.84	25000.

RUN NUMBER 107
STABILIZED DIFFUSION BURNER
METHANE
WALL-COLD AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O2 (PCT)	CO (PCT)	CO2 (PCT)	HC (PPM)
0.189	2.172	120.4	10.00	0.00		21	27	6.10	0.006	8.30	0.
0.189	2.172	120.4	10.00	0.20		19	23	6.45	0.005	8.54	0.
0.189	2.172	120.4	10.00	0.40		17	21	6.55	0.003	8.30	0.
0.189	2.172	120.4	10.00	0.60		17	21	7.00	0.004	8.07	13.
0.189	2.172	120.4	10.00	-0.60		18	24	6.50	0.009	8.30	0.
0.189	2.172	120.4	10.00	-0.40		20	27	6.10	0.009	8.54	0.
0.189	2.172	120.4	10.00	-0.20		20	23	5.80	0.009	8.54	0.

RUN NUMBER 108
STABILIZED DIFFUSION BURNER
METHANE
WALL-COLD AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O2 (PCT)	CO (PCT)	CO2 (PCT)	HC (PPM)
0.189	2.172	120.4	10.00	0.00		20	26	5.80	0.012	8.78	0.
0.189	2.172	120.4	5.00	0.00		23	36	4.30	0.473	9.02	2500.
0.189	2.172	120.4	5.50	0.00		33	46	2.90	0.734	9.51	150.
0.189	2.172	120.4	5.50	0.20		30	39	3.50	0.680	9.51	50.
0.189	2.172	120.4	5.50	0.40		24	28	5.10	1.039	8.78	100.
0.189	2.172	120.4	5.50	0.60		16	24	6.70	0.063	7.83	400.
0.189	2.172	120.4	5.50	-0.60		25	27	6.10	0.181	8.30	500.
0.189	2.172	120.4	5.50	-0.40		22	33	4.50	0.291	9.02	500.
0.189	2.172	120.4	5.50	-0.20		27	36	3.70	0.413	9.26	1000.
0.189	2.172	120.4	5.50	0.00		34	37	3.80	0.374	9.26	500.
0.189	2.172	120.4	5.00	0.00		23	33	4.00	0.707	9.02	5000.
0.189	2.172	120.4	4.50	0.00		14	24	6.20	0.927	7.60	15000.
0.189	2.172	120.4	4.00	0.00		7	14	10.50	1.011	4.86	25000.
0.189	2.172	120.4	3.50	0.00		2	6	14.50	0.734	2.70	35000.
0.189	2.172	120.4	3.00	0.00		2	3	17.50	0.239	1.25	40000.
0.189	2.172	120.4	2.00	0.00		2	1	18.50	0.032	0.45	42500.
0.189	2.172	120.4	1.00	0.00		0	1	19.00	0.014	0.21	40000.
0.189	2.172	120.4	1.00	0.20		0	1	20.25	0.037	0.25	4250.
0.189	2.172	120.4	1.00	0.10		0	1	20.25	0.026	0.25	17500.
0.189	2.172	120.4	1.00	0.30		0	1	20.00	0.026	0.62	4250.

RUN NUMBER 109
STABILIZED DIFFUSION BURNER
METHANE
WALL-COLD AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O ₂ (PCT)	CO (PCT)	CO ₂ (PCT)	HC (PPM)
0.026	0.264	106.5	10.00	0.00		35	47	1.50	0.116	4.56	500.
0.026	0.264	106.5	10.00	0.20		42	48	1.80	0.131	10.49	250.
0.026	0.264	106.5	10.00	0.40		40	50	2.20	0.063	9.99	100.
0.026	0.264	106.5	10.00	0.60		42	47	2.50	0.095	10.24	100.
0.026	0.264	106.5	10.00	-0.60		33	42	2.20	0.219	9.99	500.
0.026	0.264	106.5	10.00	-0.40		31	41	1.80	0.172	10.24	250.
0.026	0.264	106.5	10.00	-0.20		35	43	1.80	0.194	10.49	1000.
0.026	0.264	106.5	10.00	0.00		28	41	1.50	0.285	10.49	1000.
0.026	0.264	106.5	5.00	0.00		26	38	1.40	2.362	9.02	12500.
0.026	0.264	106.5	5.00	0.20		28		0.90	3.007	8.78	20000.
0.026	0.264	106.5	5.00	0.40		35	48	2.30	1.211	9.26	5000.
0.026	0.264	106.5	5.00	0.60		23	47	3.70	0.493	9.02	1500.
0.026	0.264	106.5	5.00	-0.60		13	42	3.40	0.273	9.26	1000.
0.026	0.264	106.5	5.00	-0.40		17	40	3.00	0.446	9.26	2250.
0.026	0.264	106.5	5.00	-0.20		20	43	2.50	0.844	9.51	3500.
0.026	0.264	106.5	5.00	0.00		26	42	1.90	1.597	9.26	10000.
0.026	0.264	106.5	4.00	0.00		27	43	2.40	1.973	8.78	15000.
0.026	0.264	106.5	3.00	0.00		17	43	2.75	3.403	4.64	39000.
0.026	0.264	106.5	2.00	0.00		13	51	5.90	2.724	5.15	41500.
0.026	0.264	106.5	1.00	0.00		7	19	17.25	0.181	0.73	40000.
0.026	0.264	106.5	0.80	0.00		8	12	17.25	0.181	0.72	41500.
0.026	0.264	106.5	0.60	0.00		6	11	17.00	0.209	0.61	41500.
0.026	0.264	106.5	0.40	0.00		6	9	16.00	0.066	1.33	41500.

RUN NUMBER 109 CONT
 STABILIZED DIFFUSION BURNER
 METHANE
 WALL-COLD AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O ₂ (PCT)	CO (PCT)	CO ₂ (PCT)	HC (PPM)
0.026	0.264	106.5	0.20	0.00		6	8	16.50	0.116	1.21	43500.
0.021	0.264	127.6	10.00	0.00		65	66	5.80	0.003	8.54	0.
0.021	0.264	127.6	10.00	0.20		63	65	5.70	0.003	7.83	0.
0.021	0.264	127.6	10.00	0.40		63	65	5.50	0.003	8.04	0.
0.021	0.264	127.6	10.00	0.60		62	64	6.15	0.003	7.73	0.
0.021	0.264	127.6	10.00	-0.60		63	65	6.05	0.003	7.52	0.
0.021	0.264	127.6	10.00	-0.40		64	65	5.65	0.003	7.83	0.
0.021	0.264	127.6	10.00	-0.20		63	65	5.85	0.003	8.04	0.
0.021	0.264	127.6	10.00	0.00		64	67	5.50	0.003	7.93	0.
0.021	0.264	127.6	5.00	0.00		64	70	3.50	0.291	8.87	50.
0.021	0.264	127.6	5.00	0.20		61	65	4.65	0.245	8.35	75.
0.021	0.264	127.6	5.00	0.40		54	61	5.70	0.095	8.14	15.
0.021	0.264	127.6	5.00	0.60		52	58	6.40	0.016	7.62	0.
0.021	0.264	127.6	5.00	-0.60		51	57	5.70	0.022	7.83	0.
0.021	0.264	127.6	5.00	-0.40		52	62	5.20	0.095	8.14	25.
0.021	0.264	127.6	5.00	-0.20		64	67	3.95	0.245	8.56	100.
0.021	0.264	127.6	5.00	0.00		59	68	3.50	0.352	9.98	50.
0.021	0.264	127.6	4.00	0.00		54	68	1.70	1.783	8.66	2500.
0.021	0.264	127.6	3.00	0.00		34		1.15	4.158	7.42	24400.
0.021	0.264	127.6	2.00	0.00		10		1.35	4.391	6.59	41500.
0.021	0.264	127.6	1.00	0.00		7		9.50	1.909	3.15	46500.
0.021	0.264	127.6	0.80	0.00		3		17.00	0.120	1.09	38500.
0.021	0.264	127.6	0.60	0.00		3		10.50	1.387	2.48	49000.

RUN NUMBR 109 CONT
 STABILIZED DIFFUSION BURNER
 METHANE
 WALL-COLD AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O2 (PCT)	CO (PCT)	CO2 (PCT)	HC (PPM)
0.021	0.264	127.6	0.40	2.70		3	7	16.50	0.078	1.37	38000.
0.021	0.264	127.6	0.20	2.70		3	7	16.00	0.172	1.21	44000.

RUN NUMBER 110
STABILIZED DIFFUSION BURNER
METHANE
WALL-COLD AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O ₂ (PCT)	CO (PCT)	CO ₂ (PCT)	HC (PPM)
0.019	0.264	144.5	10.00	0.00		61	64	7.65	0.003	7.21	0.
0.019	0.264	144.5	10.00	0.20		63	64	8.00	0.003	7.10	0.
0.019	0.264	144.5	10.00	0.40		63	64	8.30	0.003	6.79	0.
0.019	0.264	144.5	10.00	0.60		61	63	8.20	0.003	6.79	0.
0.019	0.264	144.5	10.00	-0.60		60	62	8.40	0.003	6.59	0.
0.019	0.264	144.5	10.00	-0.40		63	64	7.70	0.003	6.79	0.
0.019	0.264	144.5	10.00	-0.20		62	64	7.65	0.003	7.10	0.
0.019	0.264	144.5	10.00	0.00		61	65	7.40	0.003	6.90	0.
0.019	0.264	144.5	5.00	0.00		30	35	6.40	0.030	7.42	5.
0.019	0.264	144.5	5.00	0.20		33	44	6.70	0.026	7.42	0.
0.019	0.264	144.5	5.00	0.40		45	52	7.50	0.013	7.00	0.
0.019	0.264	144.5	5.00	0.60		44	51	8.30	0.004	6.79	0.
0.019	0.264	144.5	5.00	-0.60		56	60	7.60	0.004	6.90	0.
0.019	0.264	144.5	5.00	-0.40		54	61	7.20	0.005	7.10	0.
0.019	0.264	144.5	5.00	-0.20		56	64	6.60	0.009	6.38	0.
0.019	0.264	144.5	5.00	0.00		55	67	5.90	0.016	7.83	0.
0.019	0.264	144.5	4.00	0.00		62	73	4.20	0.331	8.77	0.
0.019	0.264	144.5	3.00	0.00		46		2.15	2.912	8.35	2500.
0.019	0.264	144.5	2.00	0.00		27	57	3.80	3.302	6.48	30000.
0.019	0.264	144.5	1.00	0.00		14	47	8.70	2.451	4.34	43000.
0.019	0.264	144.5	0.80	0.00		8	42	16.75	0.250	1.46	36000.
0.019	0.264	144.5	0.60	0.00		4	11	16.50	0.131	1.17	39000.
0.019	0.264	144.5	0.40	0.00		4	10	16.25	0.172	1.59	37500.

RUN NUMBER 110 CONT
 STABILIZED DIFFUSION BURNER
 METHANE
 WALL-COLD AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O ₂ (PCT)	CO (PCT)	CO ₂ (PCT)	HC (PPM)
0.019	0.264	144.5	0.20	0.00		3	9	16.00	0.079	0.30	44000.
0.032	0.264	86.0	10.00	0.00		19	40	1.65	2.724	8.35	25000.
0.032	0.264	86.0	10.00	0.20		21	43	1.48	2.070	8.35	17500.
0.032	0.264	86.0	10.00	0.40		20	43	1.50	2.070	9.14	17500.
0.032	0.264	86.0	10.00	0.60		14	43	1.75	1.973	8.25	16500.
0.032	0.264	86.0	10.00	-0.60		12	38	2.75	1.814	7.93	18500.
0.032	0.264	86.0	10.00	-0.40		13	41	2.25	1.909	8.14	20000.
0.032	0.264	86.0	10.00	-0.20		14	44	1.75	2.005	8.25	23000.
0.032	0.264	86.0	10.00	0.00		18	37	1.65	1.973	8.25	21000.
0.032	0.264	86.0	5.00	0.00		8	36	2.80	3.104	6.18	40000.
0.032	0.264	86.0	5.00	0.20		13	43	1.60	2.541	7.93	31000.
0.032	0.264	86.0	5.00	0.40		33	44	2.30	1.537	8.35	12000.
0.032	0.264	86.0	5.00	0.60		22	44	2.90	1.476	8.14	13000.
0.032	0.264	86.0	5.00	-0.60		13	41	2.10	1.446	8.46	14000.
0.032	0.264	86.0	5.00	-0.40		15	43	2.40	1.417	8.14	15000.
0.032	0.264	86.0	5.00	-0.20		20	48	2.20	1.567	8.46	15000.
0.032	0.264	86.0	5.00	0.00		16	49	2.30	2.037	8.04	28000.
0.032	0.264	86.0	4.00	0.00		12	36	3.70	3.506	5.77	42500.
0.032	0.264	86.0	3.00	0.00		10	31	5.00	3.007	4.85	45000.

RUN NUMBER 111
PREMIXED FLAT FLAME BURNER
METHANE
WALL-COLD AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O ₂ (PCT)	CO (PCT)	CO ₂ (PCT)	HC (PPM)
0.054	0.546	104.3	10.00	0.00		83	88	0.78	0.004	10.98	5.
0.054	0.546	104.3	10.00	0.20		83	90	0.65	0.003	11.23	5.
0.054	0.546	104.3	10.00	0.40		84	90	0.80	0.003	10.98	5.
0.054	0.546	104.3	10.00	0.60		84	89	0.90	0.003	10.98	5.
0.054	0.546	104.3	10.00	-0.60		74	78	1.25	0.003	10.73	5.
0.054	0.546	104.3	10.00	-0.40		75	81	1.15	0.003	10.98	5.
0.054	0.546	104.3	10.00	-0.20		78	84	0.70	0.004	10.98	5.
0.054	0.546	104.3	10.00	0.00		77	84	0.66	0.004	10.98	5.
0.054	0.546	104.3	5.00	0.00		70	82	0.74	0.037	10.98	5.
0.054	0.546	104.3	5.00	0.20		67	79	0.69	0.026	11.23	5.
0.054	0.546	104.3	5.00	0.40		67	74	0.65	0.018	11.23	5.
0.054	0.546	104.3	5.00	0.60		68	78	0.79	0.008	10.98	5.
0.054	0.546	104.3	5.00	-0.60		70	77	0.83	0.008	11.23	5.
0.054	0.546	104.3	5.00	-0.40		64	74	0.85	0.015	11.23	5.
0.054	0.546	104.3	5.00	-0.20		72	82	0.85	0.026	10.98	5.
0.054	0.546	104.3	5.00	0.00		76	87	0.84	0.026	10.98	5.
0.054	0.546	104.3	4.00	-0.20		69	74	0.95	0.054	10.98	5.
0.054	0.546	104.3	3.00	-0.20		76	91	1.10	0.099	10.73	5.
0.054	0.546	104.3	2.00	-0.20		71	87	1.20	0.163	10.73	5.
0.054	0.546	104.3	1.00	-0.20		58	79	1.50	0.311	10.24	5.
0.054	0.546	104.3	0.50	-0.20		40	62	1.60	0.626	9.99	5.
0.054	0.546	104.3	0.00	-0.20		6	15	6.80	1.720	6.44	19000.
0.054	0.546	104.3	0.10	-0.20		16	26	2.40	1.597	8.78	70.

RUN NUMBER 112
PREMIXED FURNACE BURNER
METHANE
WALL-COLD AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O2 (PCT)	CO (PCT)	CO2 (PCT)	HC (PPM)
0.225	2.067	96.3	10.00	0.00		33	37	1.05	0.008	10.98	2.
0.225	2.067	96.3	10.00	0.20		32	38	1.00	0.008	10.98	2.
0.225	2.067	96.3	10.00	0.40		32	37	1.00	0.007	10.98	2.
0.225	2.067	96.3	10.00	0.60		33	38	0.95	0.007	10.98	2.
0.225	2.067	96.3	10.00	-0.60		32	37	0.95	0.008	10.98	2.
0.225	2.067	96.3	10.00	-0.40		32	37	1.00	0.008	10.98	2.
0.225	2.067	96.3	10.00	-0.20		32	37	1.00	0.008	10.98	2.
0.225	2.067	96.3	10.00	0.00		32	37	1.00	0.008	10.98	2.
0.225	2.067	96.3	5.00	0.00		27	37	1.10	0.155	10.73	3.
0.225	2.067	96.3	5.00	-0.20		26	38	1.10	0.181	10.73	3.
0.225	2.067	96.3	5.00	-0.40		26	37	1.10	0.155	10.73	3.
0.225	2.067	96.3	5.00	-0.60		26	37	1.10	0.106	10.73	3.
0.225	2.067	96.3	5.00	0.60		31	37	1.00	0.028	10.98	3.
0.225	2.067	96.3	5.00	0.40		28	37	0.95	0.053	10.98	3.
0.225	2.067	96.3	5.00	0.20		27	37	1.00	0.106	10.73	3.
0.225	2.067	96.3	5.00	0.00		25	37	1.05	0.151	10.73	3.
0.225	2.067	96.3	4.00	0.00		21	35	1.15	0.229	10.73	3.
0.225	2.067	96.3	3.00	0.00		18	35	1.20	0.324	10.49	3.
0.225	2.067	96.3	3.00	-0.17		17	36	1.35	0.653	10.24	3.
0.225	2.067	96.3	2.00	-0.17		11	33	1.60	0.872	9.99	13.
0.225	2.067	96.3	1.00	-0.17		6	27	3.55	2.135	8.07	2500.
0.225	2.067	96.3	0.50	-0.17		6	27	3.20	2.168	7.83	3500.
0.225	2.067	96.3	0.25	-0.17		7	32	4.35	2.646	7.13	4250.

RUN NUMBER 112 CONT
 PREMIXED FURNACE BURNER
 METHANE
 WALL-COLD AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O ₂ (PCT)	CO (PCT)	CO ₂ (PCT)	HC (PPM)
0.225	2.067	96.3	0.00	-0.17		10	33	1.80	1.567	9.75	200.
0.225	2.067	96.3	-0.20	-0.17		11	34	1.35	1.182	10.24	21.

RUN NUMBER 113
PREMIXED FURNACE BURNER
METHANE
WALL-COLD AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O ₂ (PCT)	CO (PCT)	CO ₂ (PCT)	HC (PPM)
0.189	2.067	114.6	10.00	0.00		12	13	4.95	0.004	9.26	2.
0.189	2.067	114.6	10.00	0.20		11	13	4.85	0.004	9.02	2.
0.189	2.067	114.6	10.00	0.40		12	13	4.95	0.003	9.02	2.
0.189	2.067	114.6	10.00	0.60		11	12	4.90	0.002	9.02	2.
0.189	2.067	114.6	10.00	-0.60		11	12	4.80	0.002	9.02	2.
0.189	2.067	114.6	10.00	-0.40		11	13	4.90	0.003	9.02	2.
0.189	2.067	114.6	10.00	-0.20		11	12	4.80	0.003	9.02	2.
0.189	2.067	114.6	10.00	0.00		11	12	4.85	0.002	9.02	2.
0.189	2.067	114.6	10.00	0.00		9	12	4.85	0.012	9.02	2.
0.189	2.067	114.6	5.00	0.20		9	12	4.80	0.010	9.02	2.
0.189	2.067	114.6	5.00	0.40		9	11	4.80	0.008	9.02	2.
0.189	2.067	114.6	5.00	0.60		9	11	4.80	0.005	9.02	2.
0.189	2.067	114.6	5.00	-0.60		9	11	4.80	0.006	9.02	2.
0.189	2.067	114.6	5.00	-0.40		9	11	4.60	0.009	9.02	2.
0.189	2.067	114.6	5.00	-0.20		9	12	4.80	0.012	9.02	2.
0.189	2.067	114.6	5.00	0.00		9	12	4.80	0.013	9.02	2.
0.189	2.067	114.6	5.00	0.00		8	12	4.80	0.033	9.02	2.
0.189	2.067	114.6	4.00	0.00		6	12	4.80	0.085	9.02	2.
0.189	2.067	114.6	3.00	0.00		3	12	4.90	0.262	8.78	45.
0.189	2.067	114.6	2.00	0.00		2	10	6.20	1.476	7.13	3500.
0.189	2.067	114.6	1.00	0.00		2	10	6.80	1.506	6.67	5500.
0.189	2.067	114.6	0.75	0.00		2	11	6.50	1.387	7.13	5000.
0.189	2.067	114.6	0.50	0.00		3	12	6.20	1.269	7.36	3250.
0.189	2.067	114.6	0.25	0.00		3	12	5.30	0.983	8.07	1200.
0.189	2.067	114.6	0.00	0.00		3	12				

RUN NUMBER 114
PREMIXED FURNACE BURNER
METHANE
WALL-COLD AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O ₂ (PCT)	CO (PCT)	CO ₂ (PCT)	HC (PPM)
0.287	2.067	75.6	10.00	0.00		35		0.04	4.632	8.30	500.
0.287	2.067	75.6	10.00	0.20		36		0.04	4.632	8.07	500.
0.287	2.067	75.6	10.00	0.40		36		0.04	4.756	8.07	500.
0.287	2.067	75.6	10.00	0.60		35		0.04	4.632	8.30	550.
0.287	2.067	75.6	10.00	-0.60		35		0.04	4.632	8.07	600.
0.287	2.067	75.6	10.00	-0.40		35		0.04	4.632	8.07	600.
0.287	2.067	75.6	10.00	-0.20		35		0.04	4.632	8.07	600.
0.287	2.067	75.6	10.00	0.00		35		0.04	4.632	8.07	600.
0.287	2.067	75.6	5.00	0.00		37		0.04	4.882	7.83	500.
0.287	2.067	75.6	5.00	-0.20		36		0.04	4.882	7.83	575.
0.287	2.067	75.6	5.00	-0.40		34		0.04	4.756	8.07	750.
0.287	2.067	75.6	5.00	-0.60		31		0.04	4.756	8.07	850.
0.257	2.067	75.6	5.00	0.60		32		0.04	4.756	8.07	850.
0.287	2.067	75.6	5.00	0.40		34		0.04	4.632	8.07	750.
0.287	2.067	75.6	5.00	0.20		36		0.04	4.756	8.07	550.
0.287	2.067	75.6	5.00	0.00		37		0.04	4.756	7.83	450.
0.287	2.067	75.6	4.00	0.00		41		0.05	5.011	7.60	350.
0.287	2.067	75.6	3.00	0.00		48		0.07	5.011	7.60	250.
0.287	2.067	75.6	2.00	0.00		51		0.09	5.011	7.60	200.
0.287	2.067	75.6	1.00	0.00		1		4.00	4.882	5.30	18500.
0.287	2.067	75.6	1.50	0.00		26		0.80	5.276	7.13	3300.
0.287	2.067	75.6	0.50	0.00		1		4.20	4.756	5.36	21000.
0.287	2.067	75.6	0.00	0.00		7		1.60	6.765	5.36	7500.

RUN NUMBER 115
 PREMIXED FLAT FLAME BURNER
 METHANE
 WALL-HOT AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O ₂ (PCT)	CO (PCT)	CO ₂ (PCT)	HC (PPM)
0.031	0.481	161.0	5.00	0.00	1430	2	2	9.40	0.002	5.87	8.
0.031	0.481	161.0	5.00	-0.20	1430	2	2	9.40	0.002	5.97	8.
0.031	0.481	161.0	5.00	-0.40	1430	2	2	9.30	0.002	5.87	7.
0.031	0.481	161.0	5.00	-0.60	1430	2	2	9.10	0.003	5.77	7.
0.035	0.481	140.7	5.00	-0.60	1580	12	13	6.90	0.003	6.69	6.
0.035	0.481	140.7	5.00	-0.40	1580	13	14	7.00	0.004	6.79	6.
0.035	0.481	140.7	5.00	-0.20	1580	14	15	7.10	0.004	6.90	6.
0.035	0.481	140.7	5.00	-0.20	1580	13	15	7.10	0.005	6.90	6.
0.035	0.481	140.7	5.00	0.00	1580	13	15	7.10	0.004	6.90	6.
0.084	0.491	60.0	5.00	0.00	1510	2		0.03	8.380	4.24	1000.
0.084	0.491	60.0	5.00	-0.20	1510	2		0.03	8.380	4.14	780.
0.084	0.481	60.0	5.00	-0.40	1510	2		0.03	8.186	4.04	1050.
0.084	0.481	60.0	5.00	-0.60	1510	2		0.03	7.996	4.04	1550.
0.084	0.481	60.0	5.00	-0.20	1510	2		0.03	8.380	4.14	900.

RUN NUMBER 116
PREMIXED FLAT FLAME BURNER
METHANE
WALL-COLD AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O2 (PCT)	CO (PCT)	CO2 (PCT)	HC (PPM)
0.042	0.481	119.2	10.00	0.00		24	25	4.90	0.002	9.26	0.
0.042	0.481	119.2	10.00	-0.20		23	24	4.88	0.002	9.26	0.
0.042	0.481	119.2	10.00	-0.40		23	24	4.90	0.002	9.26	0.
0.042	0.481	119.2	10.00	-0.60		23	24	5.05	0.002	9.02	0.
0.042	0.481	119.2	5.00	-0.60		21	22	4.90	0.002	9.26	0.
0.042	0.481	119.2	5.00	-0.40		21	23	4.88	0.002	9.26	0.
0.042	0.481	119.2	5.00	-0.20		21	23	4.90	0.003	9.26	0.
0.042	0.481	119.2	5.00	0.00		21	24	4.90	0.002	9.26	1.
0.042	0.481	119.2	2.00	0.00		21	25	4.88	0.019	9.26	1.
0.042	0.481	119.2	1.00	0.00		18	23	4.90	0.034	9.02	0.
0.042	0.481	119.2	0.70	0.00		16	21	4.90	0.048	9.02	0.
0.042	0.481	119.2	0.50	0.00		13	19	4.95	0.067	9.02	1.
0.042	0.481	119.2	0.30	0.00		9	15	4.90	0.131	9.02	0.
0.042	0.481	119.2	0.20	0.00		7	13	5.00	0.168	9.02	1.
0.042	0.481	119.2	0.10	0.00		2	10	6.00	1.659	7.36	1250.
0.063	0.481	80.2	0.10	0.00		40		0.27	3.302	10.73	200.
0.063	0.481	80.2	0.20	0.00		48		0.07	4.045	8.78	5.
0.063	0.481	80.2	0.30	0.00		51		0.06	4.158	8.54	4.
0.063	0.481	80.2	0.50	0.00		55		0.05	4.274	8.54	3.
0.063	0.481	80.2	0.70	0.00		55		0.06	4.274	8.54	3.
0.063	0.481	80.2	1.00	0.00		57		0.05	4.391	8.30	4.
0.063	0.481	80.2	2.00	0.00		59		0.05	4.391	8.07	4.
0.063	0.481	80.2	5.00	0.00		56		0.05	3.933	8.78	3.

RUN NUMBER 116 CON
PREMIXED FLAT FLAME BURNER
METHANE
WALL-COLD AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O2 (PCT)	CO (PCT)	CO2 (PCT)	HC (PPM)
0.063	0.481	80.2	5.00	-0.20		54		0.04	3.824	9.02	1.
0.063	0.481	80.2	5.00	-0.40		53		0.05	3.610	9.26	1.
0.063	0.481	80.2	5.00	-0.60		51		0.05	3.506	9.51	1.
0.063	0.481	80.2	10.00	-0.60		49		0.14	3.403	9.26	1.
0.063	0.481	80.2	10.00	-0.40		52		0.07	3.506	9.26	1.
0.063	0.481	80.2	10.00	-0.20		54		0.06	3.506	9.26	1.
0.063	0.481	80.2	10.00	0.00		54		0.05	3.610	9.26	1.

RUN NUMBER 117
 PREMIXED FLAT FLAME BURNER
 METHANE
 WALL-HOT AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O2 (PCT)	CO (PCT)	CO2 (PCT)	HC (PPM)
0.031	0.491	161.0	5.00	-0.20	1430	3	4	9.00	0.002	6.38	0.
0.031	0.481	161.0	5.00	0.00	1430	3	5	9.00	0.001	6.38	0.
0.031	0.481	161.0	5.00	-0.40	1430	3	4	9.00	0.001	6.28	0.
0.031	0.481	161.0	5.00	-0.60	1430	3	4	9.00	0.001	6.28	0.
0.031	0.491	161.0	2.00	-0.20	1430	3	5	9.00	0.000	6.48	0.
0.031	0.481	161.0	1.00	-0.20	1430	3	5	9.00	0.003	6.48	0.
0.031	0.481	161.0	0.70	-0.20	1430	3	4	9.00	0.000	6.48	0.
0.031	0.481	161.0	0.50	-0.20	1430	2	4	9.00	0.057	6.48	0.
0.031	0.481	161.0	0.30	-0.20	1430	1	2	14.00	0.653	3.31	26000.
0.031	0.481	161.0	0.20	-0.20	1430	0	1	13.50	0.466	1.92	33000.
0.031	0.481	161.0	0.10	-0.20	1430	0	1	17.00	0.361	1.25	35000.
0.042	0.481	119.2	0.10	-0.20	1430	4	12	5.75	1.845	6.75	800.
0.042	0.481	119.2	0.20	-0.20	1430	9	20	4.75	0.239	8.35	26.
0.042	0.481	119.2	0.30	-0.20	1430	13	26	4.75	0.172	8.46	14.
0.042	0.481	119.2	0.50	-0.20	1430	21	33	4.70	0.106	8.46	4.
0.042	0.481	119.2	0.70	-0.20	1430	26	37	4.65	0.057	8.46	2.
0.042	0.481	119.2	1.00	-0.20	1430	29	40	4.60	0.050	8.46	3.
0.042	0.481	119.2	2.00	-0.20	1430	33	43	4.60	0.028	8.46	2.
0.042	0.491	119.2	5.00	0.00	1430	32	42	4.50	0.010	8.46	2.
0.042	0.481	119.2	5.00	0.00	1430	32	41	4.50	0.011	8.35	1.
0.042	0.481	119.2	5.00	-0.40	1430	29	38	4.55	0.008	8.35	1.
0.042	0.481	119.2	5.00	-0.60	1430	26	33	4.60	0.004	8.35	1.
0.042	0.481	119.2	5.00	0.00	1430	32	41	4.65	0.010	8.35	1.

RUN NUMBER 117 CONT
 PREMIXED FLAT FLAME BURNER
 METHANE
 WALL-HOT AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O ₂ (PCT)	CO (PCT)	CO ₂ (PCT)	HC (PPM)
0.042	0.481	119.2	5.00	0.00	1480	33	42	4.66	0.011	8.35	1.
0.042	0.481	119.2	5.00	0.00	1530	32	43	4.69	0.012	8.35	1.
0.042	0.481	119.2	5.00	0.00	1580	35	45	4.70	0.013	8.35	1.
0.042	0.481	119.2	5.00	0.00	1630	36	46	4.70	0.015	8.35	2.
0.042	0.481	119.2	5.00	0.00	1680	37	47	4.72	0.016	8.35	3.
0.042	0.481	119.2	5.00	0.00	1730	39	50	4.70	0.017	8.25	3.
0.042	0.481	119.2	5.00	0.00	1780	40	52	4.75	0.019	8.25	3.
0.042	0.481	119.2	5.00	-0.20	1780	40	52	4.80	0.019	8.25	2.
0.042	0.481	119.2	5.00	-0.40	1780	38	49	4.77	0.018	8.25	2.
0.042	0.481	119.2	5.00	-0.60	1780	37	48	4.75	0.016	8.14	2.
0.042	0.481	119.2	2.00	-0.60	1780	23	29	4.70	0.009	8.04	2.
0.042	0.481	119.2	1.00	-0.60	1780	17	24	4.57	0.007	7.83	2.
0.042	0.481	119.2	0.50	-0.60	1780	14	19	4.30	0.004	7.31	2.
0.043	0.481	80.2	0.50	-0.20	1825	62		0.07	4.158	7.83	3.
0.063	0.481	80.2	1.00	-0.20	1825	63		0.06	4.158	7.83	3.
0.063	0.481	80.2	5.00	-0.20	1825	60		0.06	3.933	7.73	2.
0.063	0.481	80.2	5.00	0.00	1825	57		0.06	3.933	7.62	2.

RUN NUMBER 118
PREMIXED FLAT FLAME BURNER
PROPANE
WALL-HOT AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O ₂ (PCT)	CO (PCT)	CO ₂ (PCT)	HC (PPM)
0.012	0.481	161.1	5.00	0.00	1450	4	5	9.55	0.002	7.13	0.
0.012	0.481	161.1	5.00	-0.20	1450	3	5	9.60	0.002	6.90	0.
0.012	0.481	161.1	5.00	-0.40	1450	3	4	9.50	0.002	6.90	0.
0.012	0.481	161.1	5.00	-0.60	1450	3	4	9.30	0.002	6.67	0.
0.012	0.481	161.1	2.00	-0.20	1450	3	4	10.25	0.003	7.13	2.
0.012	0.481	161.1	1.00	-0.20	1450	2	4	10.00	0.004	7.36	1.
0.012	0.481	161.1	0.50	-0.20	1450	1	3	13.75	0.473	4.14	19500.
0.012	0.481	161.1	0.25	-0.20	1450	0	1	17.50	0.250	1.17	36500.
0.012	0.481	161.1	0.10	-0.20	1450	0	1	19.50	0.155	0.43	38000.
0.012	0.481	161.1	0.10	-0.20	1475	0	0	19.00	0.168	0.61	37500.
0.012	0.481	161.1	0.10	-0.20	1500	0	0	19.00	0.172	0.63	37500.
0.012	0.481	161.1	0.10	-0.20	1525	0	0	18.75	0.190	0.67	37500.
0.012	0.481	161.1	0.10	-0.20	1565	0	0	18.70	0.199	0.70	37500.
0.033	0.481	60.8	0.10	-0.20	1565	1	0	10.25	4.756	2.38	42500.
0.033	0.481	60.8	0.25	-0.20	1565	33	0	0.08	10.539	5.05	4500.
0.033	0.481	60.8	0.50	-0.20	1565	39	0	0.08	10.539	4.95	650.
0.033	0.481	60.8	1.00	-0.20	1565	43	0	0.08	10.539	4.95	185.
0.033	0.481	60.8	2.00	-0.20	1565	46	0	0.07	10.304	4.95	90.
0.033	0.481	60.8	5.00	-0.20	1565	45	0	0.07	10.074	4.85	34.
0.033	0.481	60.8	5.00	-0.40	1565	40	0	0.07	9.848	4.75	75.
0.033	0.481	60.8	5.00	-0.60	1565	33	0	0.07	9.408	4.75	100.
0.033	0.481	60.8	5.00	0.00	1565	48	0	0.07	10.074	4.85	13.

RUN NUMBER 119
 PREMIXED FLAT FLAME BURNER
 PROPANE
 WALL-COLD AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O2 (PCT)	CO (PCT)	CO2 (PCT)	HC (PPM)
0.079	2.094	110.2	10.00	0.00		15	19	2.15	0.005	11.99	0.
0.079	2.094	110.2	10.00	-0.20		16	18	2.15	0.005	12.24	0.
0.079	2.094	110.2	10.00	-0.40		15	18	2.20	0.005	11.99	0.
0.079	2.094	110.2	10.00	-0.60		15	18	2.15	0.005	11.99	2.
0.079	2.094	110.2	5.00	-0.60		14	18	2.25	0.026	11.99	0.
0.079	2.094	110.2	5.00	-0.40		13	18	2.27	0.044	11.99	2.
0.079	2.094	110.2	5.00	-0.20		13	19	2.30	0.076	11.99	1.
0.079	2.094	110.2	5.00	0.00		12	19	2.25	0.124	11.99	2.
0.079	2.094	110.2	3.00	-0.20		10	18	2.37	0.234	11.73	2.
0.079	2.094	110.2	2.00	-0.20		7	17	2.60	0.344	11.48	2.
0.079	2.094	110.2	1.00	-0.20		5	16	2.95	0.529	11.23	15.
0.079	2.094	110.2	0.50	-0.20		4	16	3.40	0.734	10.98	13.
0.079	2.094	110.2	0.25	-0.20		3	15	3.55	0.734	10.73	2.
0.079	2.094	110.2	0.10	-0.20		2	13	3.70	0.680	10.73	2.
0.066	2.094	131.8	0.10	-0.20		0	5	6.70	0.762	8.78	50.
0.066	2.094	131.8	0.25	-0.20		1	5	6.65	0.844	8.78	200.
0.066	2.094	131.8	0.50	-0.20		1	5	6.80	1.011	8.54	1500.
0.066	2.094	131.8	1.00	-0.20		1	5	6.30	0.653	9.02	1200.
0.066	2.094	131.8	2.00	-0.20		2	5	5.80	0.151	9.75	100.
0.066	2.094	131.8	3.00	-0.20		3	5	5.75	0.046	9.99	5.
0.066	2.094	131.8	5.00	-0.20		3	5	5.70	0.015	9.99	3.
0.066	2.094	131.8	5.00	0.00		3	5	5.68	0.013	9.75	2.
0.066	2.094	131.8	5.00	-0.40		3	5	5.65	0.008	9.99	2.

RUN NUMBER 119 CONT
PREMIXED FLAT FLAME BURNER
PROPANE
WALL-COLD AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O ₂ (PCT)	CO (PCT)	CO ₂ (PCT)	HC (PPM)
0.066	2.094	131.8	5.00	-0.60		3	5	5.65	0.004	9.99	2.
0.066	2.094	131.8	10.00	-0.60		4	5	5.68	0.003	9.99	2.
0.066	2.094	131.8	10.00	-0.40		4	6	5.66	0.003	9.99	0.
0.066	2.094	131.8	10.00	-0.20		4	5	5.60	0.002	9.99	0.
0.066	2.094	131.8	10.00	0.00		4	5	5.60	0.003	9.99	0.
0.069	2.094	88.0	10.00	0.00		30		0.08	3.403	0.58	2.
0.099	2.094	88.0	10.00	-0.20		30		0.08	3.403	0.58	2.
0.099	2.094	88.0	10.00	-0.40		30		0.08	3.403	0.58	1.
0.099	2.094	88.0	10.00	-0.60		30		0.08	3.506	0.57	1.
0.099	2.094	88.0	5.00	-0.60		29		0.08	3.610	0.57	2.
0.099	2.094	88.0	5.00	-0.40		30		0.08	3.610	0.56	1.
0.099	2.094	88.0	5.00	-0.20		31		0.09	3.716	0.56	1.
0.099	2.094	88.0	5.00	0.00		32		0.09	3.824	0.56	1.
0.099	2.094	88.0	3.00	-0.20		31		0.11	3.824	0.56	10.
0.099	2.094	88.0	2.00	-0.20		31		0.13	3.610	0.56	35.
0.099	2.094	88.0	1.00	-0.20		29		0.22	3.403	0.57	80.
0.099	2.094	88.0	0.50	-0.20		28		0.32	3.104	0.58	35.
0.099	2.094	88.0	0.25	-0.20		27		0.37	2.912	0.60	3.
0.099	2.094	88.0	0.10	-0.20		25		0.40	2.724	0.60	1.

RUN NUMBER 120
PREMIXED FURNACE BURNER
PROPANE
WALL-HOT AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O ₂ (PCT)	CO (PCT)	CO ₂ (PCT)	HC (PPM)
0.012	0.481	155.5	10.00	0.00	1495	4	5	9.80	0.003	6.90	3.
0.012	0.481	155.5	10.00	-0.20	1495	4	5	9.85	0.003	6.90	4.
0.012	0.481	155.5	10.00	-0.40	1495	4	5	9.80	0.003	6.79	3.
0.012	0.481	155.5	10.00	-0.60	1495	4	4	9.80	0.004	6.90	3.
0.012	0.481	155.5	5.00	-0.60	1495	3	3	9.70	0.003	6.69	3.
0.012	0.481	155.5	5.00	-0.40	1495	3	3	9.75	0.003	6.90	3.
0.012	0.481	155.5	5.00	-0.20	1495	3	3	10.00	0.003	6.90	3.
0.012	0.481	155.5	5.00	0.00	1495	3	3	10.00	0.003	7.00	3.
0.012	0.481	155.5	2.00	-0.20	1495	2	3	10.50	0.003	7.00	3.
0.012	0.481	155.5	1.00	-0.20	1495	3	3	10.00	0.005	7.31	3.
0.012	0.481	155.5	0.70	-0.20	1495	3	3	10.00	0.008	7.31	3.
0.012	0.431	155.5	0.50	-0.20	1475	2	3	10.00	0.019	7.31	3.
0.012	0.481	155.5	0.30	-0.20	1495	1	2	13.50	0.844	4.65	17000.
0.012	0.481	155.5	0.20	-0.20	1495	0	1	16.00	0.256	2.76	35000.
0.012	0.481	155.5	0.10	-0.20	1495	0	0	18.50	0.285	1.17	38000.

RUN NUMBER 121
PREMIXED FURNACE BURNER
PROPANE
WALL-HOT AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O2 (PCT)	CO (PCT)	CO2 (PCT)	HC (PPM)
0.016	0.491	124.9	10.00	-0.20	1795	100	115	4.75	0.037	10.49	5.
0.016	0.481	124.9	10.00	0.00	1795	98	108	4.80	0.036	10.49	5.
0.016	0.481	124.9	10.00	-0.40	1795	125	140	4.80	0.039	10.24	5.
0.016	0.481	124.9	10.00	-0.60	1795	160	175	4.80	0.037	10.24	5.
0.016	0.481	124.9	5.00	-0.60	1795	52	63	4.80	0.020	10.24	4.
0.016	0.481	124.9	5.00	-0.40	1795	55	64	4.82	0.023	10.49	4.
0.016	0.481	124.9	5.00	-0.20	1795	55	65	4.90	0.021	10.49	5.
0.020	0.481	100.6	10.00	-0.20	1795	182	192	0.70	0.190	12.75	4.
0.020	0.481	100.6	10.00	-0.20	1865	240	253	0.70	0.256	12.75	4.
0.024	0.481	81.8	10.00	-0.20	1865	70		0.09	5.693	8.66	4.
0.017	0.481	117.0	10.00	-0.20	1795	145	150	3.50	0.052	11.23	2.
0.025	0.481	78.2	10.00	-0.20	1795	64		0.10	6.444	7.93	3.
0.021	0.481	95.2	10.00	-0.20	1795	135	138	0.11	1.476	12.24	2.
0.017	0.481	117.0	10.00	-0.20	1865	235	255	3.60	0.071	10.98	3.
0.021	0.481	95.2	10.00	-0.20	1865	158	160	0.14	1.357	12.50	3.
0.025	0.481	78.2	10.00	-0.20	1865	65		0.10	6.444	8.54	3.
0.020	0.481	100.6	10.00	-0.20	1865	255	260	0.70	0.262	12.75	2.

RUN NUMBER 122
STABILIZED DIFFUSION BURNER
METHANE
WALL-HOT AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O2 (PCT)	CO (PCT)	CO2 (PCT)	HC (PPM)
0.137	2.094	159.7	15.00	0.00	1450	64	82	7.80	0.003	6.07	8.
0.137	2.094	159.7	10.00	0.00	1450	75	96	6.90	0.028	7.52	6.
0.137	2.094	159.7	5.00	0.00	1450	63	83	2.80	1.597	8.56	175.
0.137	2.094	159.7	3.00	0.00	1450	3	25	9.80	2.646	4.14	42000.
0.137	2.094	159.7	4.00	0.00	1450	40	59	3.60	2.472	7.21	7500.
0.137	2.094	159.7	6.00	0.00	1450	72	89	4.50	0.546	9.46	25.
0.137	2.094	159.7	7.00	0.00	1450	72	95	5.40	0.258	8.14	5.
0.137	2.094	159.7	5.00	0.00	1450	70	90	3.20	1.357	8.56	200.
0.137	2.094	159.7	5.00	-0.20	1450	55	80	3.70	1.039	8.46	250.
0.137	2.094	159.7	5.00	-0.40	1450	43	67	5.60	0.361	7.93	300.
0.137	2.094	159.7	5.00	-0.60	1450	30	43	8.30	0.104	6.69	150.
0.137	2.094	159.7	4.00	-0.60	1450	12	31	8.85	0.219	6.38	3000.
0.137	2.094	159.7	4.00	-0.40	1450	24	48	5.70	0.789	7.42	4500.
0.137	2.094	159.7	4.00	-0.20	1450	30	55	4.30	1.814	7.93	7500.
0.137	2.094	159.7	4.00	0.00	1450	40	60	3.60	2.506	7.42	7500.

RUN NUMBER 123
 STABILIZED DIFFUSION BURNER
 METHANE
 WALL-HOT AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O ₂ (PCT)	CO (PCT)	CO ₂ (PCT)	HC (PPM)
0.137	2.094	159.7	15.00	0.00	1440	40	55	8.25	0.009	6.69	5.
0.157	2.094	139.9	15.00	0.00	1590	130	155	5.85	0.037	7.93	6.
0.157	2.094	139.9	10.00	0.00	1590	120	155	5.20	0.106	8.35	6.
0.157	2.094	139.9	5.00	0.00	1590	70	95	2.00	2.186	8.56	500.
0.157	2.094	139.9	4.00	0.00	1590	35	57	2.50	2.912	7.73	5500.
0.157	2.094	139.9	3.00	0.00	1590	0	17	12.50	1.841	3.05	35000.
0.157	2.094	139.9	4.00	0.00	1590	35	54	2.65	2.817	7.73	6500.
0.157	2.094	139.9	4.00	-0.20	1590	28	51	2.85	2.632	7.62	7500.
0.157	2.094	139.9	4.00	-0.40	1590	30	52	3.40	1.757	8.04	3850.
0.157	2.094	139.9	4.00	-0.60	1590	24	46	5.60	0.455	7.62	1750.
0.157	2.094	139.9	5.00	-0.60	1590	39	58	6.30	0.190	7.42	35.
0.157	2.094	139.9	5.00	-0.40	1590	53	75	3.80	0.955	8.46	100.
0.157	2.094	139.9	5.00	-0.20	1590	59	80	2.50	1.357	8.66	250.
0.157	2.094	139.9	5.00	0.00	1590	60	80	2.10	1.845	8.56	500.
0.157	2.094	139.9	7.00	0.00	1590	95	120	3.70	0.573	8.66	5.
0.157	2.094	139.9	9.00	0.00	1590	110	135	4.85	0.151	8.25	5.
0.157	2.094	139.9	9.00	-0.20	1590	110	130	4.95	0.143	8.25	5.
0.157	2.094	139.9	9.00	-0.40	1590	100	125	5.25	0.120	8.14	5.
0.157	2.094	139.9	9.00	-0.60	1590	90	110	5.95	0.079	7.93	5.
0.183	2.094	119.8	15.00	0.00	1775	415	475	3.70	0.143	8.87	5.
0.183	2.094	119.8	10.00	0.00	1775	265	315	2.80	0.359	9.08	5.
0.183	2.094	119.8	7.00	0.00	1775	155	190	1.60	1.783	8.87	60.
0.183	2.094	119.8	5.00	0.00	1775	72	90	0.79	3.716	7.93	1650.

RUN NUMBER 123 CONT
 STABILIZED DIFFUSION BURNER
 METHANE
 WALL-HOT AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O ₂ (PCT)	CO (PCT)	CO ₂ (PCT)	HC (PPM)
0.183	2.094	119.8	4.00	0.00	1775	30	67	1.60	4.510	6.90	10000.
0.183	2.094	119.8	3.00	0.00	1775	0	24	9.25	2.912	3.25	37500.
0.183	2.094	119.8	4.00	0.00	1775	32	58	1.50	4.510	6.90	10000.
0.183	2.094	119.8	4.00	-0.20	1775	29	56	1.60	4.391	7.10	9000.
0.183	2.094	119.8	4.00	-0.40	1775	41	63	1.45	3.104	8.14	3000.
0.183	2.094	119.8	4.00	-0.60	1775	32	57	4.30	0.899	8.14	250.
0.183	2.094	119.8	5.00	-0.60	1775	50	75	5.20	0.440	7.73	25.
0.183	2.094	119.8	5.00	-0.40	1775	65	87	2.00	1.783	8.50	300.
0.183	2.094	119.8	5.00	-0.20	1775	65	82	1.00	3.506	8.04	1500.
0.183	2.094	119.8	5.00	0.00	1775	66	80	0.82	3.933	7.73	2250.
0.183	2.094	119.8	9.00	0.00	1775	210	240	2.55	0.599	9.08	6.
0.183	2.094	119.8	9.00	-0.20	1775	210	240	2.65	0.599	9.08	5.
0.183	2.094	119.8	9.00	-0.40	1775	200	240	2.90	0.493	8.98	5.
0.183	2.094	119.8	9.00	-0.60	1775	200	240	3.45	0.304	8.87	5.
0.275	2.094	79.9	15.00	0.00	1825	110		0.11	6.444	6.28	5.
0.275	2.094	79.9	10.00	0.00	1825	100		0.11	6.444	6.07	50.
0.275	2.094	79.9	7.00	0.00	1825	71		0.20	6.765	5.87	3500.
0.275	2.094	79.9	5.00	0.00	1825	8		2.90	6.287	4.65	30000.
0.275	2.094	79.9	4.00	0.00	1825	0		6.50	4.756	3.54	38500.
0.275	2.094	79.9	3.00	0.00	1825	0		11.75	2.451	1.98	42500.
0.275	2.094	79.9	5.00	0.00	1825	9		2.70	6.931	4.65	29000.
0.275	2.094	79.9	5.00	-0.20	1825	5		3.30	6.134	4.34	32000.
0.275	2.094	79.9	5.00	-0.40	1825	20		1.85	5.984	5.46	20000.

RUN NUMBER 123 CONT
STABILIZED DIFFUSION BURNER
METHANE
WALL-HOT AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O2 (PCT)	CO (PCT)	CO2 (PCT)	HC (PPM)
0.275	2.094	79.9	5.00	-0.60	1825	65		0.77	4.158	7.42	4500.
0.275	2.094	79.9	6.00	-0.60	1825	93		0.28	4.882	7.10	2250.
0.275	2.094	79.9	6.00	-0.40	1825	56		0.72	6.287	5.87	10000.
0.275	2.094	79.9	6.00	-0.60	1825	87		0.31	5.276	6.79	3000.
0.275	2.094	79.9	6.00	-0.20	1825	32		1.05	6.931	5.25	14000.
0.275	2.094	79.9	6.00	0.00	1825	38		0.83	6.731	5.36	11500.
0.275	2.094	79.9	10.00	0.00	1825	91		0.11	6.444	6.07	50.
0.275	2.094	79.9	10.00	-0.20	1825	92		0.11	6.444	6.07	45.
0.275	2.094	79.9	10.00	-0.40	1825	93		0.11	6.287	6.18	50.
0.275	2.094	79.9	10.00	-0.60	1825	94		0.11	6.287	6.18	50.

RUN NUMBER 124
 STABILIZED DIFFUSION BURNER
 METHANE
 WALL-HOT AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O2 (PCT)	CO (PCT)	CO2 (PCT)	HC (PPM)
0.137	2.094	159.7	15.00	0.00	1955	300	350	7.50	0.049	7.36	2.
0.157	2.094	139.9	15.00	0.00	1955	520	630	6.00	0.092	8.07	4.
0.183	2.094	119.8	15.00	0.00	1955	1200	1300	3.30	0.256	9.51	5.
0.219	2.094	100.0	15.00	0.00	1955	990	1000	0.43	1.845	9.99	5.
0.275	2.094	79.9	15.00	0.00	1955	140	920	0.17	6.603	6.44	4.
0.219	2.094	100.0	15.00	0.00	1955	920	920	0.39	1.927	9.75	4.
0.219	2.094	100.0	10.00	0.00	1955	410	420	0.47	2.273	9.51	4.

RUN NUMBER 125
STABILIZED DIFFUSION BURNER
PROPANE
WALL-HOT AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O2 (PCT)	CO (PCT)	CO2 (PCT)	HC (PPM)
0.055	2.094	159.7	15.00	0.00	1425	200	235	7.10	0.043	9.02	7.
0.055	2.094	159.7	10.00	0.00	1425	200	230	5.45	0.381	9.51	8.
0.055	2.094	159.7	7.00	0.00	1425	160	190	3.30	2.168	9.99	250.
0.055	2.094	159.7	5.00	0.00	1425	100	120	1.25	5.412	8.54	5000.
0.055	2.094	159.7	4.00	0.00	1425	55		0.27	7.627	7.13	17500.
0.055	2.094	159.7	3.00	0.00	1425	15	35	2.40	7.627	5.75	37500.
0.055	2.094	159.7	4.00	0.00	1425	52		0.87	7.448	7.13	17500.
0.055	2.094	159.7	4.00	-0.20	1425	62	88	1.80	5.142	8.30	7500.
0.055	2.094	159.7	4.00	-0.40	1425	63	95	5.20	2.099	8.30	1250.
0.055	2.094	159.7	4.00	-0.60	1425	39	65	10.25	0.331	6.18	350.
0.055	2.094	159.7	5.00	-0.60	1425	49	72	11.00	0.181	5.27	225.
0.055	2.094	159.7	5.00	-0.40	1425	83	115	6.90	1.211	7.83	225.
0.055	2.094	159.7	5.00	-0.20	1425	100	125	2.95	3.104	8.66	1500.
0.055	2.094	159.7	5.00	0.00	1425	50	112	1.40	5.412	8.14	5000.
0.055	2.094	159.7	9.00	0.00	1425	185	210	5.10	0.734	9.19	25.
0.055	2.094	159.7	9.00	-0.20	1425	170	200	6.20	0.352	8.66	13.
0.055	2.094	159.7	9.00	-0.40	1425	145	170	7.90	0.172	7.73	10.
0.055	2.094	159.7	9.00	-0.60	1425	105	130	9.90	0.049	6.59	8.

RUN NUMBER 126
STABILIZED DIFFUSION BURNER
PROPANE
WALL-HOT AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O2 (PCT)	CO (PCT)	CO2 (PCT)	HC (PPM)
0.062	2.094	140.7	15.00	0.00	1610	440	495	4.95	0.374	9.99	2.
0.062	2.094	140.7	10.00	0.00	1610	325	350	3.45	1.973	9.75	75.
0.062	2.094	140.7	7.00	0.00	1610	165	195	1.75	5.142	8.30	4500.
0.062	2.094	140.7	5.00	0.00	1610	59		0.50	8.380	5.97	32500.
0.062	2.094	140.7	4.00	0.00	1610	16		1.95	8.985	4.85	42500.
0.062	2.094	140.7	3.00	0.00	1610	6		5.00	7.448	3.84	46000.
0.062	2.094	140.7	5.00	0.00	1610	54		0.90	8.380	6.07	32500.
0.062	2.094	140.7	5.00	-0.20	1610	76		2.35	5.551	7.31	12500.
0.062	2.094	140.7	5.00	-0.40	1610	81	110	7.40	1.659	7.00	12500.
0.062	2.094	140.7	5.00	-0.60	1610	49	67	13.00	0.151	4.55	150.
0.062	2.094	140.7	6.00	-0.60	1610	71	90	12.25	0.190	4.95	50.
0.062	2.094	140.7	6.00	-0.40	1610	120	150	8.00	1.387	6.90	450.
0.062	2.094	140.7	6.00	-0.20	1610	130	160	3.30	4.156	7.83	4250.
0.062	2.094	140.7	6.00	0.00	1610	105		1.25	6.765	7.31	13000.
0.062	2.094	140.7	10.00	0.00	1610	355	380	3.55	1.783	9.99	100.
0.062	2.094	140.7	10.00	-0.20	1610	355	380	4.55	1.269	9.51	35.
0.062	2.094	140.7	10.00	-0.40	1610	320	350	6.45	0.573	8.54	20.
0.062	2.094	140.7	10.00	-0.60	1610	280	305	8.80	0.181	7.36	9.

RUN NUMBER 127
STABILIZED DIFFUSION BURNER
PROPANE
WALL-HOT AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O2 (PCT)	CO (PCT)	CO2 (PCT)	HC (PPM)
0.077	2.094	114.0	15.00	0.00	1870	975	1030	1.95	1.476	10.98	7.
0.077	2.094	114.0	10.00	0.00	1870	535	570	1.75	2.472	10.24	35.
0.077	2.094	114.0	7.00	0.00	1870	255	275	1.10	5.142	8.78	1250.
0.077	2.094	114.0	5.00	0.00	1870	98		0.55	7.810	7.13	8500.
0.077	2.094	114.0	4.00	0.00	1870	47		0.88	8.779	5.98	25000.
0.077	2.094	114.0	3.00	0.00	1870	12		5.50	6.931	4.04	42500.
0.077	2.094	114.0	5.00	0.00	1870	95		0.57	7.810	6.79	8000.
0.077	2.094	114.0	5.00	-0.20	1870	140		1.20	5.412	8.04	2750.
0.077	2.094	114.0	5.00	-0.40	1870	195	203	4.60	5.412	8.56	100.
0.077	2.094	114.0	5.00	-0.60	1870	150	180	8.30	0.172	7.73	20.
0.077	2.094	114.0	6.00	-0.60	1870	275	290	6.80	0.181	8.04	15.
0.077	2.094	114.0	6.00	-0.40	1870	260	300	3.90	1.506	9.08	75.
0.109	2.094	80.4	5.00	-0.00	1870	22		1.65	9.848	4.24	41000.
0.109	2.094	80.4	10.00	0.00	1870	370		0.25	8.578	6.48	1750.
0.109	2.094	80.4	15.00	0.00	1870	800		0.35	6.765	7.31	25.
0.109	2.094	80.4	7.00	0.00	1870	175		0.61	7.272	6.79	12500.
0.109	2.094	80.4	4.00	0.00	1670	30		5.30	7.627	3.54	50000.
0.109	2.094	80.4	15.00	0.00	1870	900		0.30	6.931	6.90	50.

F-41

RUN NUMBER 128
DIFFUSION FLAME BURNER
METHANE
WALL-HOT AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O2 (PCT)	CO (PCT)	CO2 (PCT)	HC (PPM)
0.137	2.094	159.7	15.00	0.00	1440	75	93	5.80	0.124	8.07	5.
0.137	2.094	159.7	10.00	0.00	1440	66	86	5.80	0.413	7.60	35.
0.137	2.094	159.7	7.00	0.00	1440	49	76	5.60	1.125	7.36	400.
0.137	2.094	159.7	5.00	0.00	1440	30	61	5.10	1.783	6.90	2000.
0.137	2.094	159.7	4.00	0.00	1440	18	53	4.75	2.403	6.67	8500.
0.137	2.094	159.7	3.00	0.00	1440	6	36	6.30	2.912	5.05	35000.
0.137	2.094	159.7	4.00	0.00	1440	17	52	4.95	2.335	6.38	8500.
0.137	2.094	159.7	4.00	-0.20	1440	9	37	8.80	0.927	5.56	3500.
0.137	2.094	159.7	4.00	-0.40	1440	5	23	12.50	0.267	4.14	2750.
0.137	2.094	159.7	4.00	-0.60	1440	3	16	14.50	0.120	2.95	2750.
0.137	2.094	159.7	5.00	-0.60	1440	4	17	14.00	0.089	3.05	1750.
0.137	2.094	159.7	5.00	-0.40	1440	8	27	11.75	0.172	4.24	1400.
0.137	2.094	159.7	5.00	-0.20	1440	17	43	9.00	0.464	5.66	1250.
0.137	2.094	159.7	5.00	0.00	1440	28	61	5.35	1.720	6.79	2250.
0.137	2.094	159.7	9.00	0.00	1440	62	87	5.50	0.626	7.21	75.
0.137	2.094	159.7	9.00	-0.20	1440	45	63	8.25	0.229	6.07	145.
0.137	2.094	159.7	9.00	-0.40	1440	26	43	11.00	0.057	5.05	225.
0.137	2.094	159.7	9.00	-0.60	1440	14	27	13.00	0.032	3.84	250.
0.157	2.094	139.9	15.00	0.00	1590	165	195	3.80	0.789	7.83	6.
0.157	2.094	139.9	10.00	0.00	1590	95	130	4.45	1.328	7.10	125.
0.157	2.094	139.9	7.00	0.00	1590	58	92	5.10	1.597	6.79	800.
0.157	2.094	139.9	5.00	0.00	1590	34	71	3.95	2.788	6.48	9000.
0.157	2.094	139.9	4.00	0.00	1590	19	57	4.30	3.203	6.07	21000.

RUN NUMBER 128 CONT
DIFFUSION FLAKE BURNER
METHANE
WALL-HOT AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O2 (PCT)	CO (PCT)	CO2 (PCT)	HC (PPM)
0.157	2.094	139.9	3.00	0.00	1590	6	37	6.55	3.104	4.24	42500.
0.157	2.094	139.9	5.00	0.00	1590	33	70	4.50	2.541	6.48	8000.
0.157	2.094	139.9	5.00	-0.20	1590	20	54	8.50	1.068	5.36	3500.
0.157	2.094	139.9	5.00	-0.40	1590	11	33	12.50	0.239	4.14	1500.
0.157	2.094	139.9	5.00	-0.60	1590	6	22	15.00	0.071	2.85	7500.
0.157	2.094	139.9	6.00	-0.60	1590	9	24	14.25	0.059	3.15	900.
0.157	2.094	139.9	6.00	-0.40	1590	19	41	11.50	0.172	4.34	750.
0.157	2.094	139.9	6.00	-0.20	1590	33	60	8.50	1.153	5.77	750.
0.157	2.094	139.9	6.00	0.00	1590	48	83	4.40	2.302	6.69	900.
0.157	2.094	139.9	10.00	0.00	1590	80	110	2.30	2.817	7.52	6.
0.157	2.094	139.9	10.00	-0.60	1590	16	28	12.75	0.038	3.05	350.
0.157	2.094	139.9	10.00	-0.40	1590	23	38	12.75	0.037	3.64	350.
0.157	2.094	139.9	10.00	-0.20	1590	38	57	11.00	0.074	5.05	150.
0.157	2.094	139.9	10.00	0.00	1590	0		8.30	0.262	6.18	175.

RUN NUMBER 129
 STABILIZED DIFFUSION BURNER
 METHANE
 WALL-HOT AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O2 (PCT)	CO (PCT)	CO2 (PCT)	HC (PPM)
0.157	2.074	139.9	15.00	0.00	1590	145	173	7.20	0.020	7.00	1.
0.157	2.094	139.9	15.00	0.00	1590	145	180	6.60	0.072	7.21	1.
0.157	2.094	139.9	15.00	0.00	1590	130	160	7.30	0.017	6.90	2.
0.157	2.094	139.9	15.00	-0.20	1590	140	150	7.55	0.017	6.79	1.
0.157	2.094	139.9	15.00	-0.40	1590	135	160	7.70	0.016	6.69	1.
0.157	2.094	139.9	15.00	-0.60	1590	130	155	7.50	0.016	6.79	0.
0.157	2.094	139.9	15.00	0.20	1590	145	160	6.90	0.021	7.00	0.
0.157	2.094	139.9	15.00	0.40	1590	130	150	7.20	0.018	6.90	0.
0.157	2.094	139.9	15.00	0.60	1590	140	155	6.95	0.021	7.00	0.

RUN NUMBER 130
PREMIXED FLAT FLAME BURNER
METHANE
WALL-HOT AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O2 (PCT)	CO (PCT)	CO2 (PCT)	HC (PPM)
0.035	0.481	140.4	15.10	0.00	1585	25	27	6.85	0.004	6.90	1.
0.035	0.481	140.4	15.10	-0.20	1585	24	26	6.80	0.005	6.90	1.
0.035	0.481	140.4	15.10	-0.40	1585	24	27	6.80	0.006	7.00	1.
0.035	0.481	140.4	15.10	-0.60	1585	24	27	6.80	0.005	7.00	1.
0.035	0.481	140.4	10.10	-0.60	1585	21	24	6.85	0.005	7.00	1.
0.035	0.481	140.4	10.10	-0.40	1585	20	24	6.85	0.006	7.00	1.
0.035	0.481	140.4	10.10	-0.20	1585	20	23	6.90	0.005	7.00	1.
0.035	0.481	140.4	10.10	0.00	1585	19	23	6.90	0.006	7.00	1.
0.035	0.481	140.4	5.10	0.00	1585	18	22	7.00	0.006	7.10	1.
0.035	0.481	140.4	5.10	-0.20	1585	18	22	6.95	0.007	7.10	1.
0.035	0.481	140.4	5.10	-0.40	1585	18	22	6.90	0.005	7.00	1.
0.035	0.481	140.4	5.10	-0.60	1585	17	21	6.90	0.005	7.00	1.
0.035	0.481	140.4	3.10	-0.20	1585	17	22	7.00	0.009	7.10	1.
0.035	0.481	140.4	2.10	-0.20	1585	15	20	7.05	0.012	7.10	1.
0.035	0.481	140.4	1.10	-0.20	1585	13	17	7.10	0.016	7.21	1.
0.035	0.481	140.4	0.10	-0.20	1585	0	5	9.25	1.096	5.46	7000.
0.035	0.481	140.4	0.60	-0.20	1585	9	14	7.15	0.023	7.21	6.
0.035	0.481	140.4	0.35	-0.20	1585	6	11	7.20	0.050	7.10	4.

RUN NUMBER 131
PREMIXED FLAT FLAME BURNER
METHANE
WALL-HOT AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O2 (PCT)	CO (PCT)	CO2 (PCT)	HC (PPM)
0.042	0.481	120.1	15.10	0.00	1770	150	170	4.00	0.028	8.14	10.
0.042	0.481	120.1	15.10	-0.20	1770	150	170	4.00	0.030	8.25	15.
0.042	0.481	120.1	15.10	-0.40	1770	160	180	3.95	0.029	8.14	20.
0.042	0.481	120.1	15.10	-0.60	1770	165	190	3.95	0.026	8.14	28.
0.042	0.481	120.1	10.10	-0.60	1770	110	120	4.00	0.024	8.14	17.
0.042	0.481	120.1	10.10	-0.40	1770	100	115	4.00	0.026	8.04	6.
0.042	0.481	120.1	10.10	-0.20	1770	85	100	4.05	0.025	8.14	2.
0.042	0.481	120.1	5.10	0.00	1770	80	100	4.00	0.025	8.14	2.
0.042	0.481	120.1	5.10	0.00	1770	58	72	4.15	0.021	8.35	2.
0.042	0.481	120.1	5.10	-0.20	1770	60	74	4.10	0.020	8.25	2.
0.042	0.481	120.1	5.10	-0.40	1770	55	69	4.10	0.019	8.14	2.
0.042	0.481	120.1	5.10	-0.60	1770	53	65	4.10	0.017	8.14	2.
0.042	0.481	120.1	3.10	-0.20	1770	57	70	4.20	0.028	8.46	2.
0.042	0.481	120.1	2.10	-0.20	1770	52	68	4.25	0.040	8.46	1.
0.042	0.481	120.1	1.10	-0.20	1770	40	54	4.30	0.056	8.46	1.
0.042	0.481	120.1	0.10	-0.20	1770	4	19	4.60	0.374	8.04	1.
0.042	0.481	120.1	0.05	-0.20	1770	2	14	5.00	1.476	7.52	7500.
0.042	0.481	120.1	0.35	-0.20	1770	17	31	4.40	0.120	8.46	4.
0.042	0.481	120.1	0.60	-0.20	1770	25	38	4.35	0.085	8.46	3.
0.042	0.481	120.1	0.85	-0.20	1770	32	45	4.35	0.060	8.46	2.
0.065	0.481	77.5	15.10	0.00	1770	57	57	0.17	6.444	5.77	16.
0.065	0.481	77.5	15.10	-0.20	1770	55	55	0.17	6.134	5.77	15.
0.065	0.481	77.5	15.10	-0.40	1770	55	55	0.17	6.287	5.77	38.

RUN NUMBER 131 CONT
PREMIXED FLAT FLAME BURNER
METHANE
WALL-HOT AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O2 (PCT)	CO (PCT)	CO2 (PCT)	HC (PPM)
0.065	0.481	77.5	15.10	-0.60	1770	55		0.17	6.134	5.66	43.
0.065	0.481	77.5	10.10	-0.60	1770	59		0.17	5.984	5.56	20.
0.065	0.481	77.5	10.10	-0.40	1770	61		0.17	5.984	5.66	4.
0.065	0.481	77.5	10.10	-0.20	1770	62		0.17	5.984	5.66	3.
0.065	0.481	77.5	10.10	0.00	1770	62		0.17	6.134	5.66	2.
0.065	0.481	77.5	5.10	0.00	1770	67		0.17	6.134	5.77	2.
0.065	0.481	77.5	5.10	-0.20	1770	69		0.17	6.134	5.77	2.
0.065	0.481	77.5	5.10	-0.40	1770	68		0.17	5.984	5.66	2.
0.065	0.481	77.5	5.10	-0.60	1770	66		0.17	5.984	5.56	2.
0.065	0.481	77.5	3.10	-0.20	1770	70		0.17	6.287	5.87	2.
0.065	0.481	77.5	2.10	-0.20	1770	71		0.17	6.444	5.97	2.
0.065	0.481	77.5	1.10	-0.20	1770	71		0.18	6.444	5.97	2.
0.065	0.481	77.5	0.10	-0.20	1770	23		2.65	5.837	4.95	14000.
0.065	0.481	77.5	0.35	-0.20	1770	62		0.19	6.287	6.18	15.
0.065	0.481	77.5	0.15	-0.20	1770	55		0.20	6.134	6.18	40.
0.045	0.481	110.7	15.10	0.00	1865	390	430	1.95	0.113	8.77	15.
0.045	0.481	110.7	15.10	-0.20	1865	400	440	1.90	0.102	8.66	25.
0.045	0.481	110.7	15.10	-0.40	1865	430	480	1.90	0.106	8.56	55.
0.045	0.481	110.7	15.10	-0.60	1865	450	490	1.85	0.099	8.56	65.
0.045	0.481	110.7	10.10	-0.60	1865	237	270	1.90	0.073	8.35	55.
0.045	0.481	110.7	10.10	-0.40	1865	210	250	1.90	0.071	8.35	33.
0.045	0.481	110.7	10.10	-0.20	1865	175	210	2.00	0.077	8.46	4.
0.045	0.481	110.7	10.10	0.00	1865	170	200	2.00	0.078	8.66	3.

RUN NUMBER 131 CONT
PREMIXED FLAT FLAME BURNER
METHANE
WALL-HOT AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O2 (PCT)	CO (PCT)	CO2 (PCT)	HC (PPM)
0.045	0.481	110.7	5.10	0.00	1865	100	135	2.10	0.059	8.87	2.
0.045	0.481	110.7	5.10	-0.20	1865	110	130	2.10	0.060	8.77	2.
0.045	0.481	110.7	5.10	-0.40	1865	100	130	2.10	0.055	8.66	1.
0.045	0.481	110.7	5.10	-0.60	1865	95	120	2.05	0.050	8.46	1.
0.045	0.481	110.7	3.10	-0.20	1865	95	120	2.20	0.076	9.08	1.
0.045	0.481	110.7	2.10	-0.20	1865	80	110	2.25	0.092	9.19	2.
0.045	0.481	110.7	1.10	-0.20	1865	60	90	2.30	0.147	9.75	2.
0.045	0.481	110.7	0.10	-0.20	1865	5	25	2.70	0.734	9.26	2.
0.045	0.481	110.7	0.25	-0.20	1865	15	35	2.60	0.267	9.51	2.
0.050	0.481	100.8	15.10	-0.20	1945	800	840	0.83	0.285	9.26	27.
0.050	0.481	100.8	15.10	-0.60	1945	920	950	0.77	0.298	9.26	40.
0.050	0.481	100.8	10.10	-0.60	1945			0.84	0.250	9.26	26.
0.050	0.481	100.8	10.10	-0.20	1945	565	620	0.93	0.245	9.51	17.
0.050	0.481	100.8	5.10	-0.20	1945	210	390	1.00	0.181	9.75	4.
0.050	0.481	100.8	15.10	0.00	1945	775	830	0.80	0.304	9.75	10.
0.050	0.481	100.8	15.10	-0.20	1945	810	865	0.80	0.304	9.02	13.
0.050	0.481	100.8	15.10	-0.40	1945	900	960	0.80	0.291	8.78	13.
0.050	0.481	100.8	15.10	-0.60	1945	945	980	0.75	0.291	9.02	12.
0.045	0.481	110.7	15.10	-0.20	1945	1425	1500	2.45	0.124	8.07	10.
0.042	0.481	120.1	15.10	-0.20	1945	1580	1750	3.60	0.092	7.83	10.
0.038	0.481	131.0	15.10	-0.20	1945	1725	1900	5.10	0.066	6.79	10.
0.035	0.481	140.4	15.10	-0.20	1945	1750	1975	6.15	0.054	6.38	10.
0.033	0.481	151.3	15.10	-0.20	1945	1800	2025	7.30	0.043	5.77	10.

RUN NUMBER 131 CONT
 PREMIXED FLAT FLAME BURNER
 METHANE
 WALL-HOT AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O2 (PCT)	CO (PCT)	CO2 (PCT)	HC (PPM)
0.055	0.481	90.8	15.10	-0.20	1945	210	230	0.25	2.369	7.52	9.
0.063	0.481	79.9	15.10	-0.20	1945	90	90	0.25	5.142	5.66	15.

RUN NUMBER 132
PREMIXED FURNACE BURNER
METHANE
WALL-HOT AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O ₂ (PCT)	CO (PCT)	CO ₂ (PCT)	HC (PPM)
0.031	0.481	159.5	15.00	0.00	1440	2	2	8.80	0.002	5.66	0.
0.031	0.481	159.5	10.00	0.00	1440	1	2	8.80	0.003	5.77	13.
0.031	0.481	159.5	5.00	0.00	1440	1	2	8.80	0.002	5.77	17.
0.031	0.481	159.5	3.00	0.00	1440	0	1	12.00	0.304	3.84	15000.
0.031	0.481	159.5	2.00	0.00	1440	0	1	17.00	0.076	1.46	33000.
0.031	0.481	159.5	1.00	0.00	1440	0	0	18.00	0.010	0.81	34500.
0.031	0.481	159.5	4.00	0.00	1440	1	2	9.05	0.072	5.65	350.
0.031	0.481	159.5	3.50	0.00	1440	0	2	9.70	0.155	5.15	4000.
0.031	0.481	159.5	3.35	0.00	1440	0	1	10.25	0.219	4.85	7000.
0.031	0.481	159.5	15.00	0.00	1440	1	2	8.95	0.003	5.66	25.
0.031	0.481	159.5	15.00	-0.20	1440	1	2	8.95	0.003	5.66	15.
0.031	0.481	159.5	15.00	-0.40	1440	1	2	8.90	0.002	5.66	10.
0.031	0.481	159.5	15.00	-0.60	1440	1	2	8.90	0.003	5.66	11.

RUN NUMBER 133
PREMIXED FURNACE BURNER
METHANE
WALL-HOT AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O2 (PCT)	CO (PCT)	CO2 (PCT)	HC (PPM)
0.137	2.094	159.7	15.00	0.00	1440	2	3	8.65	0.003	5.97	0.
0.137	2.094	159.7	10.00	0.00	1440	2	3	8.70	0.003	5.87	0.
0.137	2.094	159.7	5.00	0.00	1440	1	3	8.80	0.042	5.87	400.
0.137	2.094	159.7	4.00	0.00	1440	0	2	10.00	0.285	5.15	6000.
0.137	2.094	159.7	3.00	0.00	1440	0	1	13.75	0.413	3.05	25000.
0.137	2.094	159.7	2.00	0.00	1440	0	1	16.00	0.185	1.64	33500.
0.137	2.094	159.7	1.00	0.00	1440	0	0	18.00	0.031	0.69	35000.
0.137	2.094	159.7	3.50	0.00	1440	0	2	11.50	0.413	4.14	15500.
0.137	2.094	159.7	4.50	0.00	1440	0	2	9.00	0.151	5.66	2100.
0.137	2.094	159.7	15.00	0.00	1440	2	3	8.70	0.003	5.97	25.
0.137	2.094	159.7	15.00	-0.20	1440	2	3	8.70	0.003	5.97	22.
0.137	2.094	159.7	15.00	-0.40	1440	2	3	8.70	0.003	5.97	16.
0.137	2.094	159.7	15.00	-0.60	1440	2	3	8.60	0.003	5.97	11.
0.137	2.094	159.7	3.75	0.00	1440	0	2	10.50	0.359	4.44	10000.
0.137	2.094	159.7	3.35	0.00	1440	0	2	12.25	0.429	3.74	17500.
0.157	2.094	139.9	15.00	-0.60	1590	7	10	6.60	0.008	6.90	2.
0.157	2.094	139.9	15.00	-0.40	1590	7	10	6.60	0.007	6.90	2.
0.157	2.094	139.9	15.00	-0.20	1590	7	9	6.60	0.008	6.90	2.
0.157	2.094	139.9	15.00	0.00	1590	7	10	6.60	0.008	6.90	2.
0.157	2.094	139.9	10.00	0.00	1590	6	8	6.60	0.008	6.90	2.
0.157	2.094	139.9	5.00	0.00	1590	5	7	6.65	0.010	6.90	1.
0.157	2.094	139.9	4.00	0.00	1590	5	7	6.65	0.021	6.90	15.
0.157	2.094	139.9	3.00	0.00	1590	0	6	7.30	0.285	6.38	2500.

RUN NUMBER 133 CONT
 PREMIXED FURNACE BURNER
 METHANE
 WALL-HOT AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O2 (PCT)	CO (PCT)	CO2 (PCT)	HC (PPM)
0.157	2.094	139.9	2.00	0.00	1590	0	3	13.25	0.816	3.05	30000.
0.157	2.094	139.9	1.00	0.00	1590	0	1	17.00	0.163	1.01	36000.
0.157	2.094	139.9	3.50	0.00	1590	2	6	6.60	0.073	6.90	350.
0.157	2.094	139.9	2.50	0.00	1590	0	4	9.35	0.789	5.05	12000.
0.157	2.094	139.9	2.75	0.00	1590	0	5	8.00	0.546	5.27	6000.
0.157	2.094	139.9	2.25	0.00	1590	0	3	11.00	0.844	3.94	22500.

RUN NUMBER 134
PREMIXED FURNACE BURNER
METHANE
WALL-HOT AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O ₂ (PCT)	CO (PCT)	CO ₂ (PCT)	HC (PPM)
0.035	0.481	140.4	15.00	0.00	1585	10	12	7.40	0.003	6.59	0.
0.035	0.481	140.4	15.00	-0.20	1585	10	12	7.40	0.003	6.48	0.
0.035	0.481	140.4	15.00	-0.40	1585	9	12	7.35	0.004	6.59	0.
0.035	0.481	140.4	15.00	-0.60	1585	9	12	7.35	0.004	6.59	0.
0.035	0.481	140.4	10.00	0.00	1585	6	8	7.40	0.003	6.69	0.
0.035	0.481	140.4	5.00	0.00	1585	4	6	7.50	0.003	6.69	0.
0.035	0.481	140.4	4.00	0.00	1585	3	5	7.50	0.005	6.79	0.
0.035	0.481	140.4	3.00	0.00	1585	3	5	7.50	0.007	6.79	0.
0.035	0.481	140.4	2.00	0.00	1585	3	5	7.50	0.019	6.79	0.
0.035	0.481	140.4	1.00	0.00	1585	2	5	7.25	0.029	6.90	0.
0.035	0.481	140.4	0.00	0.00	1585	2	5	7.10	0.063	7.00	0.
0.035	0.481	140.4	-0.05	0.00	1585	1	5	7.10	0.068	7.10	0.
0.077	0.481	65.3	15.00	0.00	1600	1		0.24	9.194	4.14	8.
0.077	0.481	65.3	15.00	-0.20	1600	1		0.24	9.194	3.84	5.
0.077	0.481	65.3	15.00	-0.40	1600	1		0.24	9.194	3.84	4.
0.077	0.481	65.3	15.00	-0.60	1600	1		0.24	9.194	3.84	3.
0.077	0.481	65.3	10.00	0.00	1600	0		0.24	8.985	3.94	500.
0.077	0.481	65.3	5.00	0.00	1600	0		0.71	8.186	3.94	12000.
0.077	0.481	65.3	4.00	0.00	1600	0		7.10	5.275	2.45	37500.
0.077	0.481	65.3	3.00	0.00	1600	0		12.75	2.724	1.41	42000.
0.077	0.481	65.3	4.50	0.00	1600	0		3.50	6.765	3.25	32000.
0.077	0.481	65.3	7.50	0.00	1600	0		0.23	8.779	3.94	2100.
0.077	0.481	65.3	6.00	0.00	1600	0		0.23	8.578	4.04	4500.

RUN NUMBER 135
 PREMIXED FURNACE BURNER
 PROPANE
 WALL-HOT AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O ₂ (PCT)	CO (PCT)	CO ₂ (PCT)	HC (PPM)
0.014	0.481	138.8	15.00	0.00	1625	13	18	7.70	0.008	7.42	0.
0.014	0.481	138.8	15.00	-0.20	1625	14	19	7.70	0.008	7.42	0.
0.014	0.481	138.8	15.00	-0.40	1625	16	21	7.70	0.007	7.31	0.
0.014	0.481	138.8	15.00	-0.60	1625	17	22	7.70	0.008	7.31	0.
0.014	0.481	138.8	10.00	0.00	1625	6	8	7.75	0.006	7.31	0.
0.014	0.481	138.8	5.00	0.00	1625	3	5	7.70	0.004	7.42	0.
0.014	0.481	138.8	4.00	0.00	1625	3	5	7.70	0.004	7.42	0.
0.014	0.481	138.8	3.00	0.00	1625	2	5	7.70	0.030	7.42	200.
0.014	0.481	138.8	2.00	0.00	1625	0	1	16.00	0.291	2.37	34000.
0.014	0.481	138.8	2.50	0.00	1625	0	3	11.00	0.421	5.36	17000.
0.014	0.481	138.8	2.75	0.00	1625	0	4	8.50	0.229	6.79	4000.
0.014	0.481	138.8	2.25	0.00	1625	0	1	13.50	0.438	3.64	30000.

RUN NUMBER 136
PREMIXED FURNACE BURNER
PROPANE
WALL-HOT AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O2 (PCT)	CO (PCT)	CO2 (PCT)	HC (PPM)
0.062	2.094	140.7	15.00	0.00	1610	12	15	6.50	0.012	8.25	9.
0.062	2.094	140.7	15.00	-0.20	1610	12	15	6.50	0.013	8.25	8.
0.062	2.094	140.7	15.00	-0.40	1610	12	15	6.50	0.012	8.25	5.
0.062	2.094	140.7	15.00	-0.60	1610	12	16	6.45	0.014	8.25	5.
0.062	2.094	140.7	10.00	0.00	1610	9	13	6.65	0.011	8.14	3.
0.062	2.094	140.7	5.00	0.00	1610	7	11	6.60	0.019	8.25	2.
0.062	2.094	140.7	4.00	0.00	1610	6	10	6.60	0.055	8.25	75.
0.062	2.094	140.7	3.00	0.00	1610	0	6	8.25	0.707	7.00	7000.
0.062	2.094	140.7	2.00	0.00	1610	0	2	14.75	0.734	3.05	34000.
0.062	2.094	140.7	2.50	0.00	1610	0	4	11.25	0.899	5.05	25000.
0.062	2.094	140.7	3.25	0.00	1610	1	6	8.00	0.352	7.62	4000.
0.062	2.094	140.7	3.50	0.00	1610	1	6	7.50	0.267	7.52	2500.
0.062	2.094	140.7	3.75	0.00	1610	2	7	7.20	0.172	7.73	1000.
0.062	2.094	140.7	2.75	0.00	1610	0	3	10.50	0.899	5.35	18000.
0.062	2.094	140.7	2.90	0.00	1610	0	4	9.50	0.762	5.87	14000.

RUN NUMBER 137
PREMIXED FURNACE BURNER
PROPANE
WALL-HOT AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O2 (PCT)	CO (PCT)	CO2 (PCT)	HC (PPM)
0.072	2.094	120.9	15.00	0.00	1795	74	91	3.80	0.063	10.98	3.
0.072	2.094	120.9	15.00	-0.20	1795	72	91	3.85	0.060	10.98	2.
0.072	2.094	120.9	15.00	-0.40	1795	72	92	3.85	0.064	10.73	2.
0.072	2.094	120.9	15.00	-0.60	1795	73	94	3.85	0.062	10.98	4.
0.072	2.094	120.9	15.00	0.00	1795	69	90	3.85	0.062	10.98	3.
0.072	2.094	120.9	10.00	0.00	1795	43	63	3.85	0.054	10.98	3.
0.072	2.094	120.9	5.00	0.00	1795	24	37	3.95	0.091	10.98	1.
0.072	2.094	120.9	4.00	0.00	1795	19	24	4.10	0.151	10.73	1.
0.072	2.094	120.9	3.00	0.00	1795	16	21	4.30	0.245	10.73	1.
0.072	2.094	120.9	2.00	0.00	1795	9		4.50	0.374	10.49	2.
0.072	2.094	120.9	1.00	0.00	1795	5		4.80	0.626	10.24	15.
0.072	2.094	120.9	0.00	0.00	1795	1		5.70	1.537	9.02	100.

RUN NUMBER 138
PREMIXED FURNACE BURNER
PROPANE
WALL-HOT AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O ₂ (PCT)	CO (PCT)	CO ₂ (PCT)	HC (PPM)
0.016	0.481	120.8	15.00	0.00	1795	200	240	5.20	0.028	9.26	2.
0.016	0.481	120.8	15.00	-0.20	1795	170	210	5.20	0.024	9.26	2.
0.016	0.481	120.8	15.00	-0.40	1795	160	200	5.20	0.025	9.26	4.
0.016	0.481	120.8	15.00	-0.60	1795	160	200	5.20	0.025	9.26	5.
0.016	0.481	120.8	10.00	0.00	1795	70	95	5.40	0.016	9.26	2.
0.016	0.481	120.8	5.00	0.00	1795	10	20	5.55	0.012	9.51	2.
0.016	0.481	120.8	3.00	0.00	1795	8	16	5.70	0.024	9.75	1.
0.016	0.481	120.8	1.00	0.00	1795	4	11	6.40	0.139	9.51	1.
0.016	0.481	120.8	0.00	0.00	1795	2	6	7.40	0.239	9.02	50.
0.016	0.481	120.8	2.00	0.00	1795	7	13	5.95	0.043	9.75	1.
0.016	0.481	120.8	2.50	0.00	1795	7	13	5.85	0.030	9.75	1.
0.016	0.481	120.8	2.75	0.00	1795	7	14	5.95	0.035	9.75	1.
0.016	0.481	120.8	1.50	0.00	1795	6	12	6.20	0.064	9.51	1.

RUN NUMBER 139
PREMIXED FURNACE BURNER
METHANE
WALL-HOT AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O2 (PCT)	CO (PCT)	CO2 (PCT)	HC (PPM)
0.042	0.481	120.1	15.00	0.00	1770	95	120	4.25	0.019	8.54	5.
0.042	0.481	120.1	15.00	-0.20	1770	95	120	4.25	0.017	8.30	6.
0.042	0.481	120.1	15.00	-0.40	1770	100	130	4.20	0.021	8.30	8.
0.042	0.481	120.1	15.00	-0.60	1770	105	130	4.20	0.021	8.30	8.
0.042	0.481	120.1	10.00	0.00	1770	31	48	4.35	0.010	8.54	2.
0.042	0.481	120.1	5.00	0.00	1770	12	23	4.60	0.012	9.26	1.
0.042	0.481	120.1	3.00	0.00	1770	11	21	4.60	0.022	9.02	1.
0.042	0.481	120.1	1.00	0.00	1770	10	20	4.50	0.116	9.26	1.
0.042	0.481	120.1	0.00	0.00	1770	7	18	4.30	0.172	9.26	1.
0.042	0.481	120.1	2.00	0.00	1770	11	19	4.60	0.039	9.02	1.
0.042	0.481	120.1	1.50	0.00	1770	10	19	4.60	0.060	9.26	1.

RUN NUMBER 140
PREMIXED FURNACE BURNER
METHANE
WALL-HOT AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O2 (PCT)	CO (PCT)	CO2 (PCT)	HC (PPM)
0.183	2.094	119.8	15.00	0.00	1775	45	66	3.75	0.045	9.26	7.
0.183	2.094	119.8	15.00	-0.20	1775	47	67	3.75	0.045	9.26	7.
0.183	2.094	119.8	15.00	-0.40	1775	49	69	3.70	0.044	9.26	6.
0.183	2.094	119.8	15.00	-0.60	1775	49	70	3.70	0.045	9.26	6.
0.183	2.094	119.8	10.00	0.00	1775	31	47	3.75	0.038	9.26	5.
0.183	2.094	119.8	5.00	0.00	1775	19	31	3.80	0.063	9.26	3.
0.183	2.094	119.8	3.00	0.00	1775	15	29	3.90	0.185	9.26	2.
0.183	2.094	119.8	2.00	0.00	1775	10	26	4.00	0.291	9.26	3.
0.183	2.094	119.8	1.00	0.00	1775	4	22	4.30	1.011	8.78	200.
0.183	2.094	119.8	0.00	0.00	1775	2	18	4.25	1.068	8.78	5000.

RUN NUMBER 141
 PREMIXED FLAT FLAME BURNER
 METHANE
 WALL-COLD AIR PREHEAT-NONE

FUEL FLOW (CFM)	AIR FLOW (CFM)	PCT STOIC AIR	AXIAL DIST (IN)	RADIAL DIST (IN)	WALL TEMP (C)	NO (PPM)	NOX (PPM)	O ₂ (PCT)	CO (PCT)	CO ₂ (PCT)	HC (PPM)
0.050	0.481	100.8	12.60	0.00		47	48	0.53	0.219	10.98	5.
0.050	0.481	100.8	12.60	0.20		49	49	0.36	0.181	11.23	5.
0.050	0.481	100.8	12.60	0.40		49	49	0.35	0.190	11.48	4.
0.050	0.481	100.8	12.60	0.60		49	49	0.32	0.172	11.99	4.
0.050	0.481	100.8	12.60	0.60		49	49	0.30	0.163	11.48	4.
0.050	0.481	100.8	9.60	0.60		49	49	0.31	0.151	11.23	4.
0.050	0.481	100.8	9.60	0.40		49	49	0.26	0.139	11.48	3.
0.050	0.481	100.8	9.60	0.20		49	49	0.26	0.143	11.23	3.
0.050	0.481	100.8	9.60	0.00		50	51	0.26	0.181	11.23	4.
0.050	0.481	100.8	4.60	0.20		55	56	0.45	0.324	10.98	4.
0.050	0.481	100.8	2.60	0.20		57	60	0.66	0.599	10.73	4.
0.050	0.481	100.8	1.60	0.20		49	60	0.79	0.789	10.49	4.
0.050	0.481	100.8	0.60	0.20		40	50	1.00	0.789	10.49	4.
0.050	0.481	100.8	0.30	0.20		23	35	1.20	0.983	10.24	4.
0.050	0.481	100.8	0.20	0.20		16	29	1.25	1.125	9.99	25.